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Image Velocity Sensor Subsystem (IVSS) Study Final Report

Volume III: SUBSYSTEM DEFINITION

NOVEMBER 1964

Prepared for

HEADQUARTERS, SPACE SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
Los Angeles, California

Contract No.: AF04(695)-656

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Volume III: SUBSYSTEM DEFINITION

Prepared by the

Advanced Systems Research Staff

IBM Space Guidance Center, Owego, New York

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Abstract

The five volumes making up this Technical Documentary Report describe the results of a 3-month study of the Image Velocity Sensor Subsystem conducted for the Space Systems Division of the Air Force Systems Command under Contract AF04(695)-656. This study involved the analyses, parametric studies, simulations, preliminary design efforts, and planning necessary to develop meaningful definitions of the experiments and experimental hardware required to fulfill the objectives of the MOL program.

Volume I summarizes the entire study. Volume II presents the results of an elemental simulation program conducted to assess man's ability to perform the planned experiments. Simulation plans are also discussed in this volume. The results of trade-off and equipment design analyses are given in Volume IV, while Volume V presents detailed plans for conducting subsequent phases of the IVSS program.

In general, this study has demonstrated the basic feasibility of the proposed MOL experiments, indicated the high degree of precision that human participation can provide to the system, and developed designs and plans compatible with MOL program guidelines.

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Image Velocity Sensor Subsystem (IVSS) Study
Final Report
SSD TR 64 237

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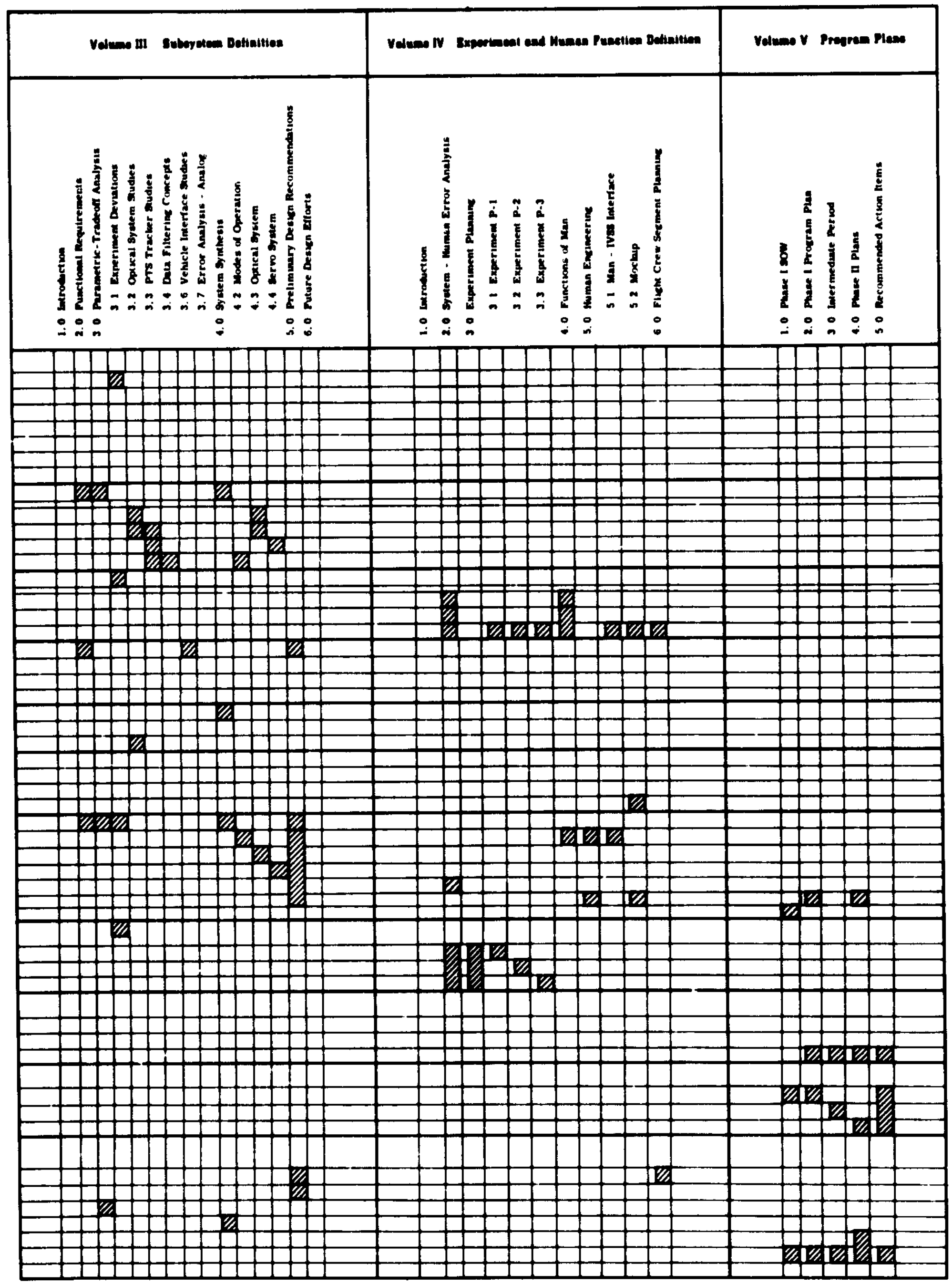
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This volume presents the results of Tasks 2, 4, 5, and 7 which pertain to the system definition of the IVSS. (Volume V contains the general IVSS system specification, and seven equipment contract end item (CEI) specifications are appended to the statement of work for phase I.) These specifications also appear in Volume I, which also lists the long lead items for IVSS.

Section 2 of Volume III identifies all of the function requirements for preparing, conducting and evaluating the experiment. Those functions with a critical impact on the system design received the most attention during this pre-Phase I portion of the study.

Section 3 contains all the pertinent analyses and trade-off data used in Section 4 to synthesize and select the recommended IVSS configuration. This recommendation is detailed in Section 5. Section 6 describes certain aspects of the system design tasks to be performed during Phase I.

1.0 Introduction and Summary

The Image Velocity Sensor Subsystem (IVSS) comprises (1) a pointing tracking scope (PTS) and associated servo scanners, (2) two optically coupled cameras, (3) displays and controls, (4) in-space experiment evaluation equipment, (5) a power supply unit, and (6) associated software. A set of star trackers and a cine camera is included as optical equipment. These seven groupings of contract end items (CEI) have been documented in the CEI detail specifications contained in Volumes I and V. Also contained in these Volumes is the IVSS general specification.

The IVSS, as presently configured and described in Section 5, has the following physical characteristics (not including optional equipment):

- Weight - 680 pounds
- Power - 705 watts (average)
- Volume - 40 cubic feet (15 cubic feet outboard)

Three modes of operation are presently conceived for the IVSS:

- The Primary Mode - a digital instrumentation that solves all of the equations necessary to meet criteria tracking for any single target.
- Analog Instrumentation - enables the astronaut to meet the acquistion and tracking criteria, but does not perform the additional calculations that the primary digital mode is capable of.
- Extended Capability Mode - a digital instrumentation that employs additional equipment (star trackers) to maintain an accurate knowledge of vehicle attitude and position from one target to another. This knowledge would be required in a multiple-target mission, where allowable acquisition and tracking times are minimal.

It is recommended that the primary digital and the analog instrumentations be implemented for IVSS. The extended capability mode can be obtained by incorporating star trackers and more computer capacity. The digital computer storage requirements for implementing all three experiments are as follows:

- Primary Mode: 8, 500 instructions
- Extended Capability: 18, 970 instructions.

The prominent features of the IVSS are now described. The optical elements of the PTS consist of an 8-inch aperture lens with a 36-inch focal length, which is capable of yielding 2. 2 arc seconds resolution at a contrast ratio of 1. 6:1. The servo scanners should meet a dynamic pointing accuracy of about 10 arc seconds, and an angular rate error of 2. 5 arc seconds/second. It appears that for the primary mode of operation, horizon sensors, coupled with either rate-integrating gyros or a drift meter mode is sufficient to align the vehicle to the orbital plane for precise tracking.

The important tasks that need be accomplished in phase Ib are as follows:

- The most critical design effort of the next two phases is concerned with the tracking servo, which is mounted outside the vehicle, and which will operate in a hard vacuum and be subject to high temperature variations. Of critical importance here are the torquing and suspension elements, plus the gimbal angle sensing and feedback elements.
- In concert with the servo, a hand controller design must be evolved that is consistent with orbital space operations. Signals from the controller will pass through an optimum set of gains and transfer functions to the tracking servo for precise tracking.
- Other important design efforts will concern the structural and environmental considerations associated with the optical system mounted outside the vehicle.
- The complete definition of equations will be finalized. Special attention will be given to data filtering for precise tracking, where the role of the filter is to uncouple the various error sources and help the man meet criteria tracking. This filtering study is also related to the experimental evaluation studies that must be conducted in depth to establish and finalize the optical design requirements and in-space evaluation requirements.

2.0 IVSS Functional Requirements

2.1 Scope

This section of the report translates the requirements expressed in the statement of work into functional requirements for the experimental system. These functional requirements are in turn translated into equipment performance requirements in Section 3. The following extracted from the statement of work constitute the basic requirements of the IVSS design.

"The image velocity sensor subsystem should be capable of providing accurate data regarding the angles and angular velocity of a target line-of-sight with respect to the spacecraft. Such angular rate data may be used to apply the necessary corrective motion to either slow down or immobilize the image for visual inspection by the astronaut, or to provide synchronized motion of a recording medium to enhance the resolution of the recorded image. The experimental image velocity sensor subsystem design should permit assessment of man's capability to track, compatible with line-of-sight angular rate determination, to an accuracy of better than 0.2 percent."

2.1.1 Requirements

The requirements for each of the three MOL experiments to be performed using this subsystem are subsequently described.

2.1.1.1 P-1: Acquisition and Tracking of Ground Targets

The objectives of this experiment are to evaluate man's performance in acquiring pre-assigned ground targets and tracking them to an accuracy compatible with the requirements for precise image velocity determination. Pre-selected test targets both in and out of the orbital plane will be acquired and tracked from a nominal altitude of 100 to 160 n mi. These targets may include military air fields, operational missile sights, AMR, ships, surface submarines, specially prepared target areas, and various targets of opportunity. The illumination conditions may vary from twilight (pre-dawn) to a sun angle of approximately 40 degrees. Contrast ratios down to 1.2 at the objective should be assumed. Photographs obtained with a coupled camera during acquisition and tracking, and/or upon completion of the tracking run, will be used to evaluate man's proficiency in performing the experiment.

2.1.1.2 P-2: Acquisition and Tracking of Space Targets

The objectives of this experiment are (1) to evaluate man's ability to acquire and track satellite targets for the purpose of providing precise image velocity determination during fly-by maneuvers (oblique crossing),

and, (2) to evaluate man's ability to acquire and track targets in a coplanar orbit in order to provide rendezvous guidance. The image velocity of the space target will be determined during the tracking run. Photographs obtained with a coupled camera during the tracking run will be used to evaluate the astronaut's performance in determining image velocity.

The space targets may be assumed to be a sphere, cone, cylinder, or a combination of these elements, with or without appendages such as antenna, photo cell arrays, or sensor elements. The average reflectance of the target vehicles may be assumed to be 0.5. The variance of the reflectance along the surface of any given target may be assumed to vary from 0.03 to 0.8. Relative velocity between the MOL and the target vehicles should be assumed to be as high as 35,000 feet/second (90-degree inclined orbits) for the fly-by experiment. In addition, the targets may be rotating with peripherai speeds as high as 30 feet/second.

2.1.1.3 P-3: Direct Viewing for Ground and Sea Targets

The objective of this experiment is to evaluate man's ability to scan and acquire land targets of opportunity, to scan and detect ships and surface submarines, and to examine these naval craft for classification. To classify certain land and sea targets, the astronaut will arrest all image motion, change to magnification for detail viewing, and then note his observations on a direct voice recorder. In some cases, he may obtain verification pictures with a coupled camera. In the case of sea targets, prelocated target vessels will be employed, and the astronaut will record his impressions of ship class, heading, and any uniquely identifying features.

2.1.2 Subsystem Characteristics

The Image Velocity Sensor Subsystem consists primarily of (1) a direct-viewing pointing and tracking telescope (PTS) with coupled camera, and (2) a tracking servo system used in conjunction with the general-purpose computer. The MOL vehicle, which will contain the IVSS, will be subjected to launch environments and sustained orbital environments. The vehicle and equipment is expected to perform reliably for up to 1 month.

The laboratory vehicle will include one or more pressurized sections, plus an unpressurized section. Each pressurized section, approximately 10 feet in diameter and 7 feet long, will provide a "shirt-sleeve" environment. The dimensions of the unpressurized section will be approximately 10 by 10 feet. The first flight test of this subsystem is assumed to be late 1967. Applicable spacecraft performance parameters are as listed below:

- Altitude: 100 to 160 n mi
- Inclination: less than 40 degrees

- Altitude Error: ±3 n mi. (3 σ SPADATS value)
- Attitude Error: 0.25 to 0.30 degree, mean error in each axis.

A pressurized module of the MOL vehicle will house all or a major portion of the stationary refractive optical elements of the IVSS, as well as the coupled camera and general purpose-computer. The scanning elements will either project (after launch) beyond the walls of the pressurized vehicle compartment, or be located in a vacuum module just behind a suitable aperture of the vehicle. An unobstructed view over the major portion of the half space below the vehicle is required.

2.2 IVSS Functional Flow Block Diagrams

The functions required to carry out the above three experiments are detailed in Figures 2-1 through 2-3. The top level functions, Figure 2-1, can be separated into preparing, conducting, and evaluating the experiments. Since the experiment preparation and evaluation functions are detailed in Volume IV, a third-level indenture flow, Figure 2-3, is shown only for conducting the experiment.

The large number of functions to be performed for all three experiments precludes a detailed description for each one. Instead, the approach taken is to identify and concentrate on those functions which severely affect the IVSS equipment configuration.

The list below shows the primary equipment/facility categories detailed in the following subsections. These sections emphasize the requirements derived from the functional flow diagrams.

- Telescopic subsystems
- Servo scanner subsystem
- Recording cameras and film processors
- Computers
- Displays and controls
- Data acquisition and recording subsystem
- Vehicle system interface
- Experiment evaluation subsystem
- Ground support facilities

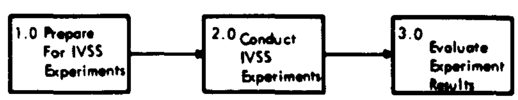


Figure 2-1. Top Level Functions

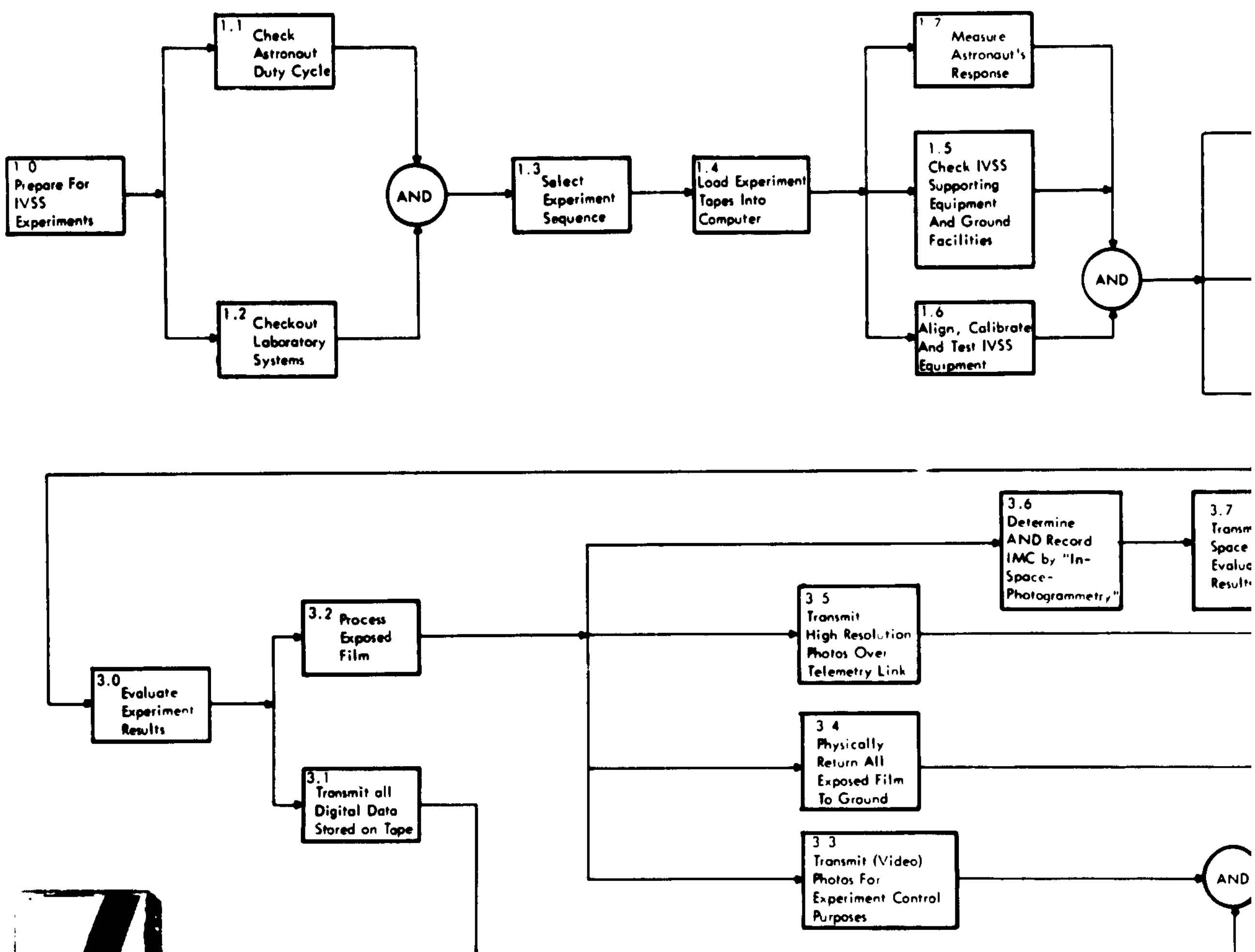
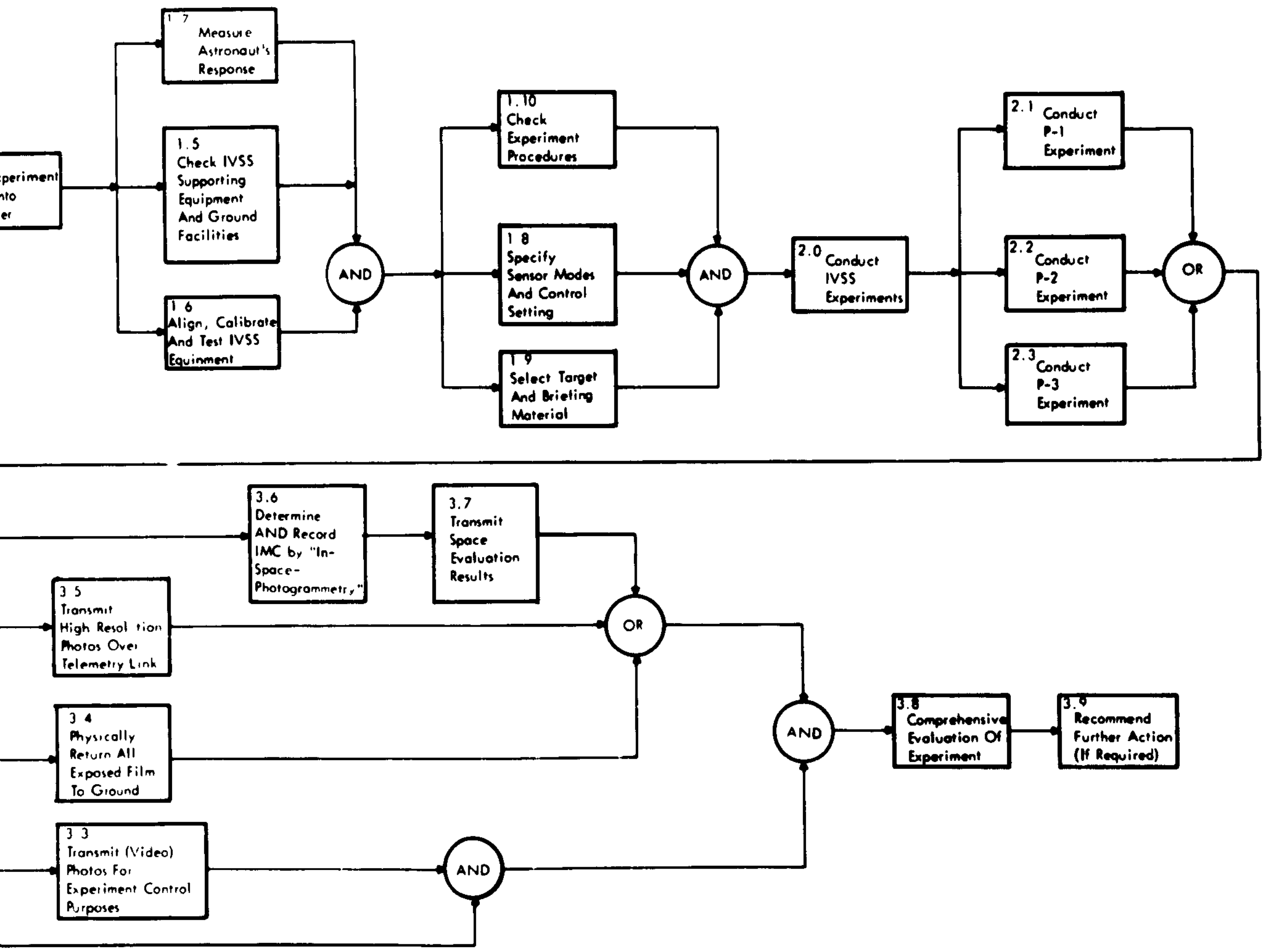
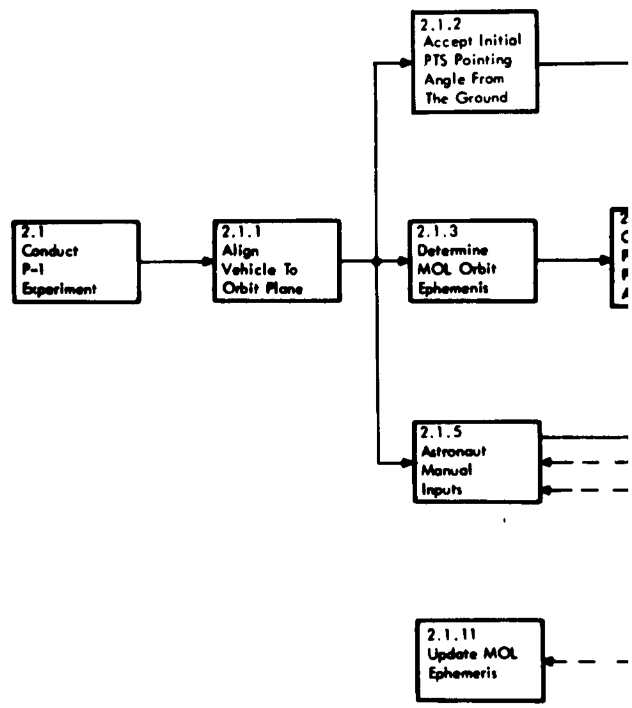


Figure 2-2. Second Level Indenture Functions



periment
nto
er
1.7 Measure Astronaut's Response
1.5 Check IVSS Supporting Equipment And Ground Facilities
1.6 Align, Calibrate And Test IVSS Equipment
AND
1.10 Check Experiment Procedures
1.8 Specify Sensor Modes And Control Setting
1.9 Select Target And Briefing Material
AND
2.0 Conduct IVSS Experiments
2.1 Conduct P-1 Experiment
2.2 Conduct P-2 Experiment
2.3 Conduct P-3 Experiment
OR
3.6 Determine AND Record IMC by "In-Space-Photogrammetry"
3.7 Transmit Space Evaluation Results
3.5 Transmit High Resol tion Photos Over Telemetry Link
OR
3.4 Physically Return All Exposed Film To Ground
AND
3.8 Comprehensive Evaluation Of Experiment
3.9 Recommend Further Action (If Required)
3.3 Transmit (Video) Photos For Experiment Control Purposes
AND

2



2.1 Conduct P-1 Experiment
2.1.1 Align Vehicle To Orbit Plane
2.1.2 Accept Initial PTS Pointing Angle From The Ground
2.1.3 Determine MOL Orbit Ephemeris
2.1.5 Astronaut Manual Inputs
2.1.11 Update MOL Ephemeris

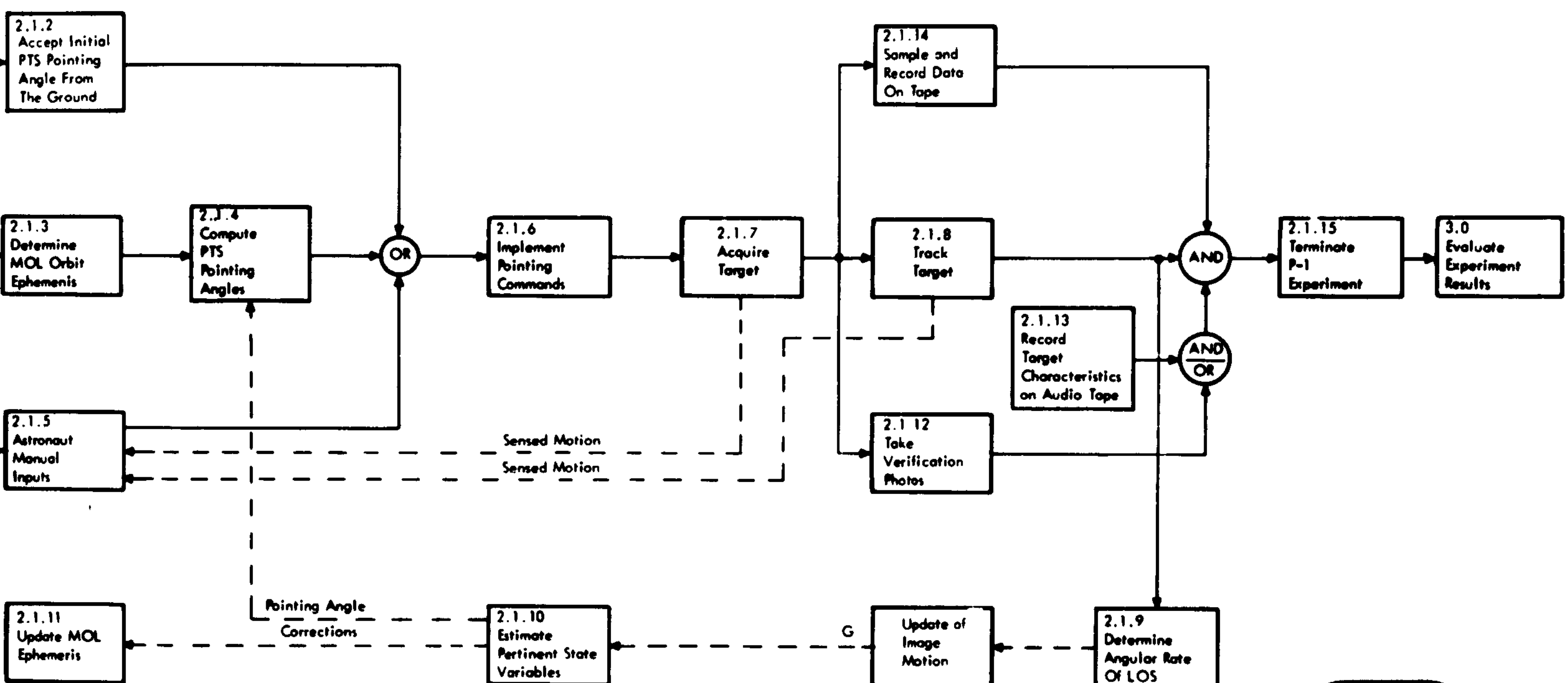
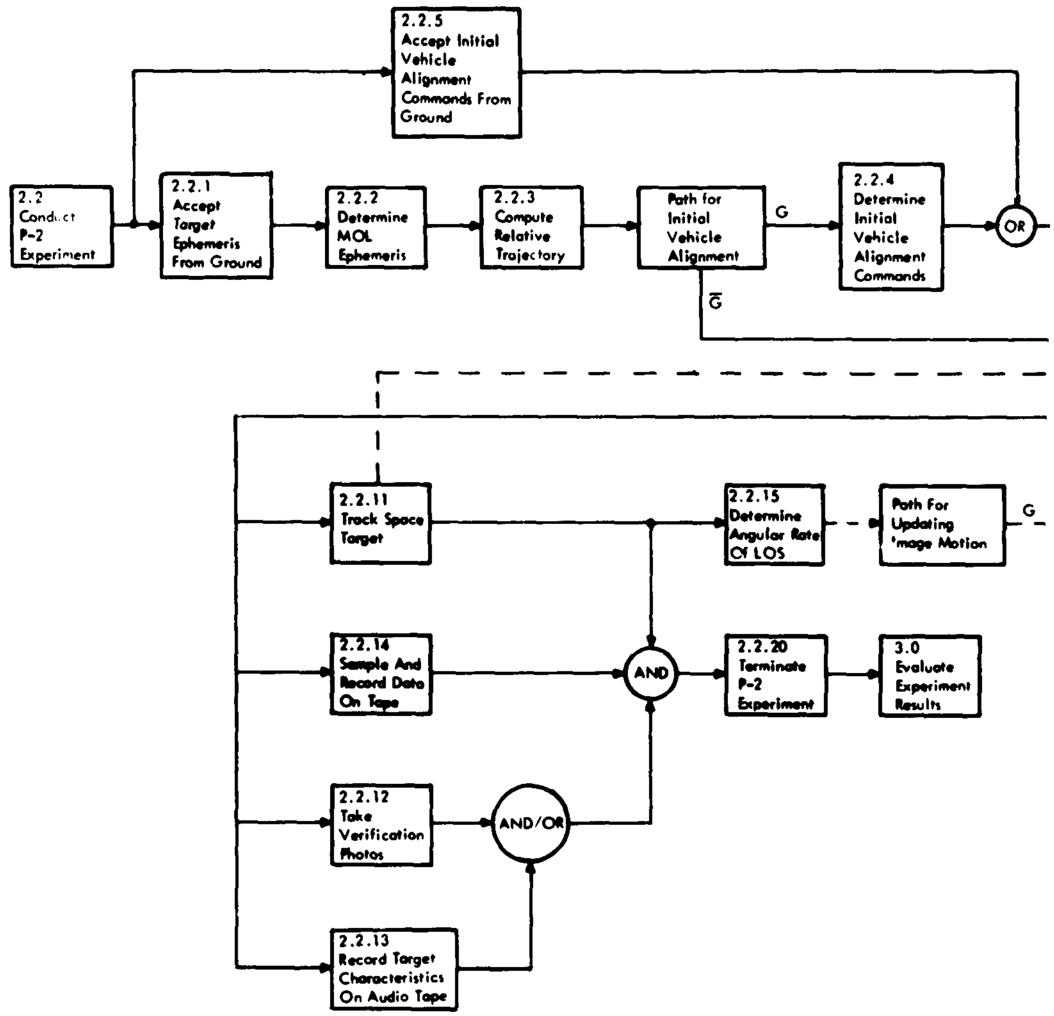


Figure 2-3. Third Level Indenture Functions (Sheet 1 of 3)


2.2.5 Accept Initial Vehicle Alignment Commands From Ground
2.2 Conduct P-2 Experiment
2.2.1 Accept Target Ephemeris From Ground
2.2.2 Determine MOL Ephemeris
2.2.3 Compute Relative Trajectory
Path for Initial Vehicle Alignment
G
2.2.4 Determine Initial Vehicle Alignment Commands
OR
Ḡ
2.2.11 Track Space Target
2.2.15 Determine Angular Rate Of LOS
Path For Updating Image Motion
G
2.2.14 Sample And Record Data On Tape
AND
2.2.20 Terminate P-2 Experiment
3.0 Evaluate Experiment Results
2.2.12 Take Verification Photos
AND/OR
2.2.13 Record Target Characteristics On Audio Tape

7

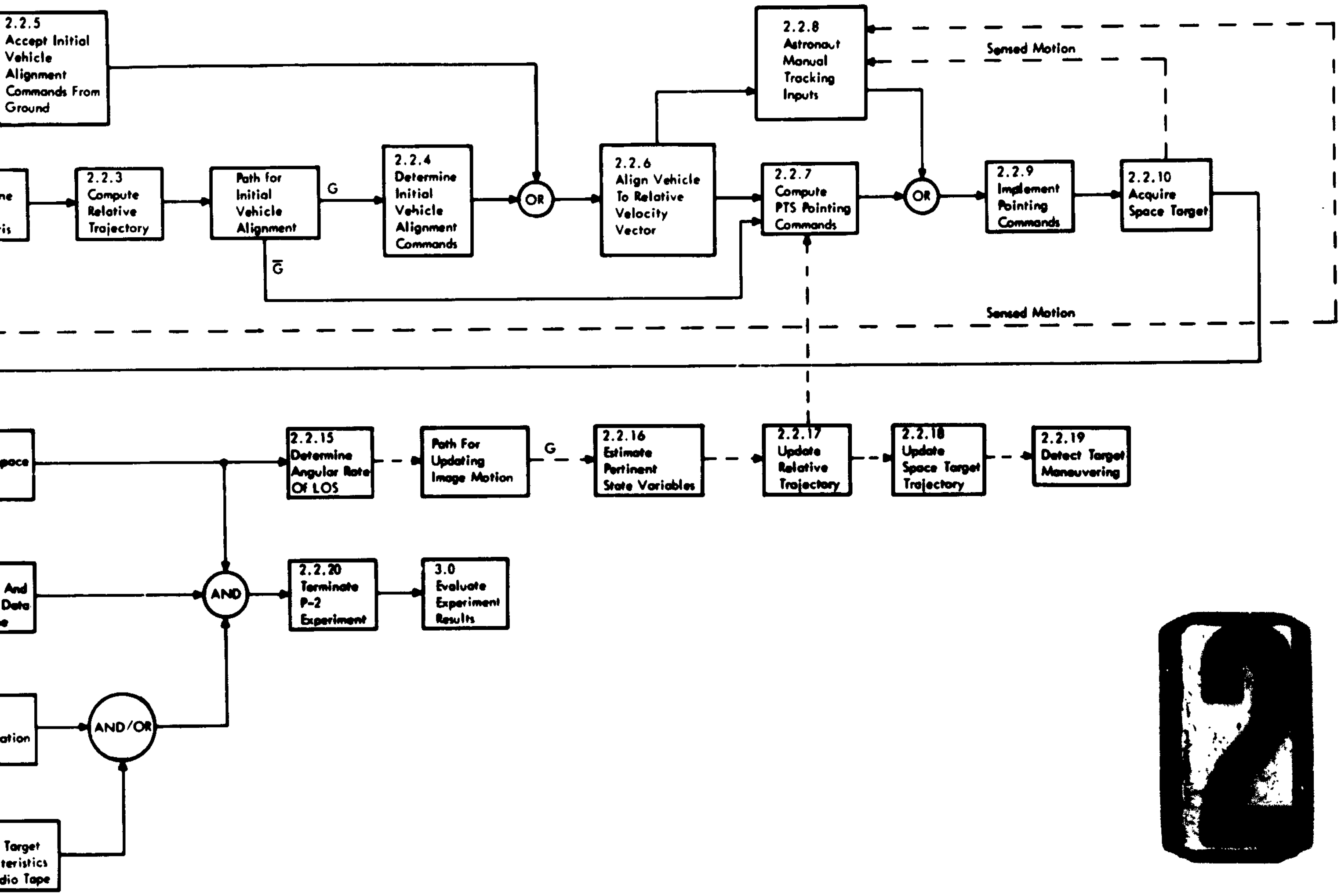
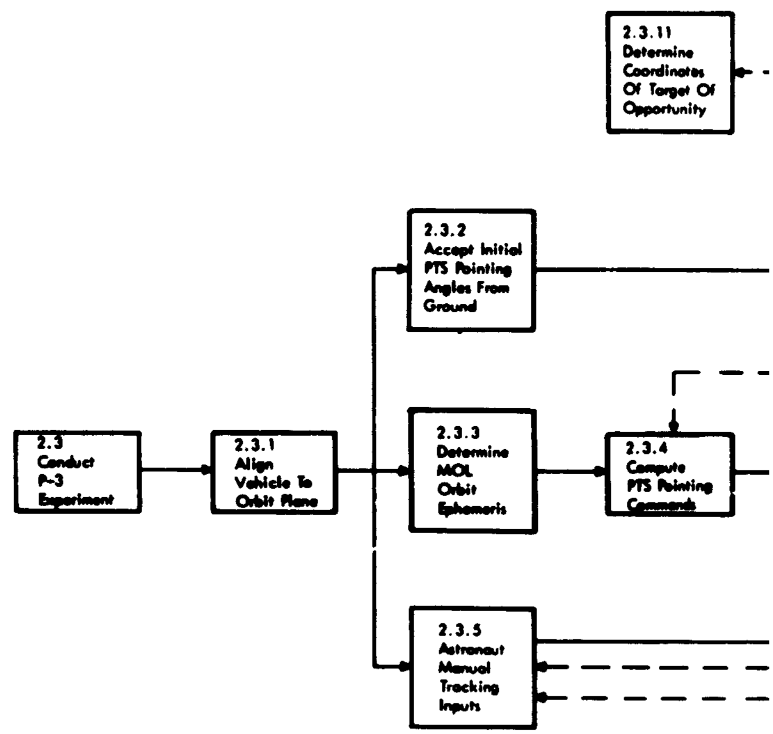


Figure 2-3. Third Level Indenture Functions (Sheet 2 of 3)


2.3.11 Determine Coordinates Of Target Of Opportunity
2.3.2 Accept Initial PTS Pointing Angles From Ground
2.3 Conduct P-3 Experiment
2.3.1 Align Vehicle To Orbit Plane
2.3.3 Determine MOL Orbit Ephemeris
2.3.4 Compute PTS Pointing Commands
2.3.5 Astronaut Manual Tracking Inputs

7

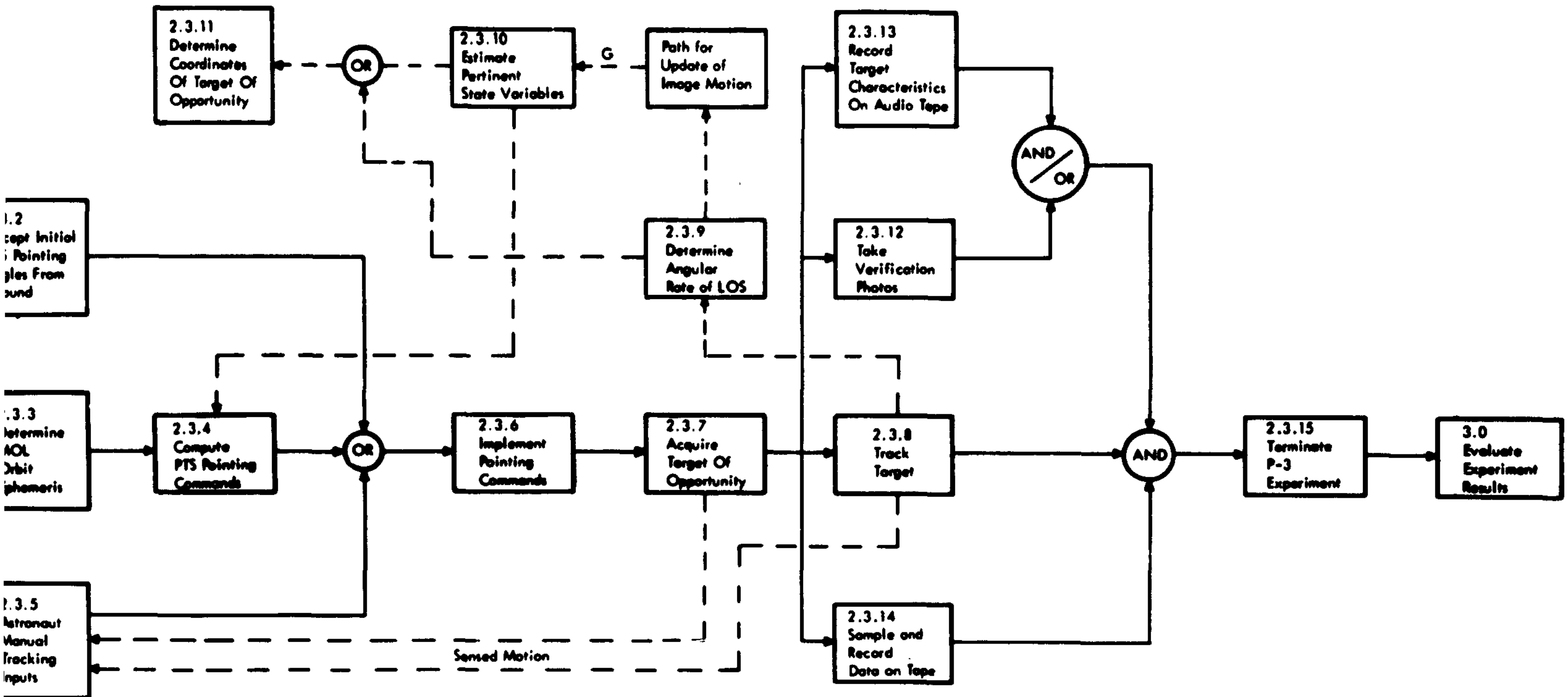


Figure 2-3. Third Level Indenture Functions (Sheet 3 of 3)

2.3 Derived Functional Requirements

2.3.1 Telescopic Subsystem Design

The requirements for the telescopic subsystem are as follows:

- A design that permits ease of equipment alignment and calibration, and which allows equipment testing prior to experimental use
- Sufficient visual resolution to allow position fixing by the astronaut
- Resolution and field of view which allows either acquisition of a preselected target with the projected errors in initial pointing, or acquisition of targets of opportunity
- Sufficient visual resolution to allow tracking of targets
- Aperture size and resolution consistent with camera requirements
- Photo-optical resolution compatible with evaluation of image motion compensation, based on restrictions placed on minimum sample times for this evaluation
- Visual resolution which allows for classification of targets
- Safety features, such as sun sensors and sun shades which prevent damage to the telescope

2.3.2 Servo Scanner Subsystem

The requirements for the servo scanner subsystem are as follows:

- Alignment and calibration to a known vehicle and/or celestial reference
- Provision for testing commanded rate response
- Implementation of pointing commands
- Automatic scan capability which allows for acquisition of a variety of targets
- Tracking smoothness
- Dynamics permitting acquisition and tracking of both ground and space targets
- Provisions for determining line-of-sight rates
- Extreme reliability in hard vacuum conditions
- Capability of being commanded manually and/or automatically

2.3.3 Recording Cameras and Film Processor

Most requirements placed on the recording cameras and film processor equipment result from the necessity for producing "hard-copy" experimental data.

The cameras must

- Have provisions for alignment, calibration and testing
- Record the astronaut's performance during the target acquisition phase
- Record the tracking of targets, providing sufficient photo-optical resolution to permit evaluation of image motion compensation photogrammetrically
- Have sufficient resolution to allow verification of the astronaut's classification of targets
- Have sufficient film available to comprehensively evaluate the astronaut's performance

The processing portion of this subsystem must

- Process the exposed film without loss of photographic detail
- Provide completed photographs (negatives) that can be stored and/or returned to the ground without excessive special handling
- Have nontoxic photographic processing chemicals.

2.3.4 Computer

The computer, one of the most heavily used MOL subsystems, must perform a variety of tasks for the IVSS experiment, including:

- Equipment check-out and calibration
- Preparation and control of the experiment
- Sampling the console and sensor inputs
- Solving the IVSS equations

Because of the impact that the equations have on the computer, the last category can be broken down into the following computations and control functions:

- Calibrating and testing the IVSS
- Vehicle alignment to orbit plane, which implies an interface with the attitude control system
- Sun angle
- MOL orbit ephemeris (initial and updated)
- PTS pointing angles for initial pointing, tracking, and scanning for ground and space targets
- PTS pitch and roll rates
- Time-to-go for target acquisition, target track time, and minimum line-of-sight distance
- Tracking servo input commands
- Briefing film orientation
- Visual Evaluation Tracker (VET) film control, error signal summation

- Processing manual tracking inputs
- Relative motion filter
- Space target relative trajectory (initial and updated)
- Vehicle alignment for fly-by
- Camera shutter and exposure control

2.3.5 Displays and Controls

Because the display and control consoles provide the astronaut/equipment interface, provisions must be made for control of every subsystem critical to the IVSS experiment. The console must provide the following functions:

- Mode switches for aligning, calibrating, and testing IVSS subsystems
- Experiment sequence mode switch
- VET control
- Briefing presentation unit control
- Auxiliary tape control
- Attitude control system interface
- PTS magnification, attenuation, filter, polarization, reticle, and focus
- PTS control and display of pointing angles
- Camera filter, frame rate, and exposure control; display of frame number, film type, and exposure time
- PTS mode and function control (ground or space target, update)
- Track mode, target select, and scan mode select switches
- Mode select (PTS extended capabilities, PTS alternate, VET)
- Display of target parameters, time to target, and target track time
- Film evaluation projector control
- Voice tape control; display of tape remaining and recording level
- Computer data insert and display panels
- Hand control for the PTS
- Malfunction test panel for IVSS equipment.

2.3.6 Data Acquisition and Recording Subsystem

To provide for a controlled reconstruction of the experiment, the data acquisition and recording subsystem must provide for sampling and recording all data pertinent to the IVSS experiment. This subsystem must therefore sample and record

- All console mode and function switches
- All console control switches
- Hand control shaft angles

- Sensor data such as time, PTS gimbal angles, PTS servo loop error signal, star tracker gimbal angles, briefing slide perspective, horizon sensor outputs, and inertial reference unit output
- Target and vehicle parameters, (latitude and longitude, target time to go, and track time.)
- Space target minimum line-of-sight distance
- Digital Command System (DCS) update parameters (sample only)
- Photograph tag data (frame number, pertinent sensor, and console data)
- Calibration data (PTS commanded rate response)
- Unit malfunction indicators
- Astronaut's voice depicting his impressions of target characteristics or other data.

2.3.7 Vehicle System Interface

The requirements for IVSS equipment interface with other MOL subsystems can be summarized by noting those requirements listed previously for IVSS equipment which affect the vehicle systems. These include the use of

- Vehicle systems to align, calibrate, and check out IVSS equipment
- Computer and auxiliary tape during IVSS experiments for computations and program storing
- DCS link to update MOL ephemeris and time, and to give space target ephemeris
- Telemetry subsystem for recording and transmitting all experimental data
- Attitude control system, attitude reference unit, and horizon sensors to maintain vehicle attitude reference
- Environmental control system

2.3.8 Experiment Evaluation Subsystem

This subsystem must have the capability to permit evaluation of the following both in the MOL and on the ground:

- Accuracy in alignment and calibration
- Man's performance during acquisition
- Man's performance during tracking
- Man's contribution to image motion compensation
- Man's ability to detect maneuvering space targets.

2.3.9 Ground Support Facilities

These facilities must monitor and check

- Astronaut duty cycles
- MOL and ground systems check-out
- Experiment sequence
- Experimental procedures

In addition, ground support facilities must receive or recover

- All telemetered IVSS data
- Control photos via a video link
- High-resolution photos (by telemetry)
- Data capsules (if used).

Ground support is also required to

- Supply initial pointing angles for P-1 and P-3 on request
- Supply updated time and MOL ephemeris
- Supply space target ephemeris
- Supply vehicle alignment commands for P-2
- Comprehensively evaluate the experiments.

3.0 Parametric and Trade-off Analysis

This section presents the salient data and results of the investigations conducted during the IVSS study. These results, combined with the design criteria, form a logical base for designing the IVSS equipment to comply with the functional requirements stipulated in Section 2.0. The data presented in this section pertains to the following:

- Telescopic system
- Coupled camera
- Tracking servos
- Data filtering approaches
- IVSS equations and computer analysis
- Vehicle interface studies

In order to present these in the proper light, a brief discussion of the experiments follows.

3.1 Experiment Deviation

The objective of the IVSS experiments to be conducted in MOL is to evaluate man's performance in acquiring and tracking preassigned ground and space targets, and surface targets of opportunity. The significant factors which underlie the definition of the experiments and which affect the evaluation of man's performance, are discussed in the following paragraphs.

3.1.1 Acquisition and Tracking of Ground Targets

The information flow for the acquisition and tracking of terrestrial targets is depicted in Figure 3-1. Knowledge of the MOL ephemeris, from ground tracking or autonomous navigation, and of the target's geographic coordinates, allows precomputation of the motion of the Line-of-Sight (LOS) to the target. This in turn allows the computation of: (1) the orientation of the target locus relative to the MOL, (2) the orientation of the PTS scanning plane, and (3) the initial pointing angles of the PTS and its associated angular rate profile. The astronaut, upon acquisition of the target with the viewfinder slaved to the general purpose digital computer, generates error signals to the PTS pitch and roll gimbal servos. These error signals are proportional to the displacement of the target image from the crosshairs; and are used to stabilize the image presentation, and to update the MOL's orbital parameters using linear perturbation theory employing Kalman, least squares, or a more restricted data filter.

3.1.1.1 Acquisition of Ground Targets

Factors that affect the acquisition of ground targets are:

- Pointing accuracy and field of view
- Image quality and nature of target
- Observation time

- Weather and illumination
- Briefing material (see Volume II)

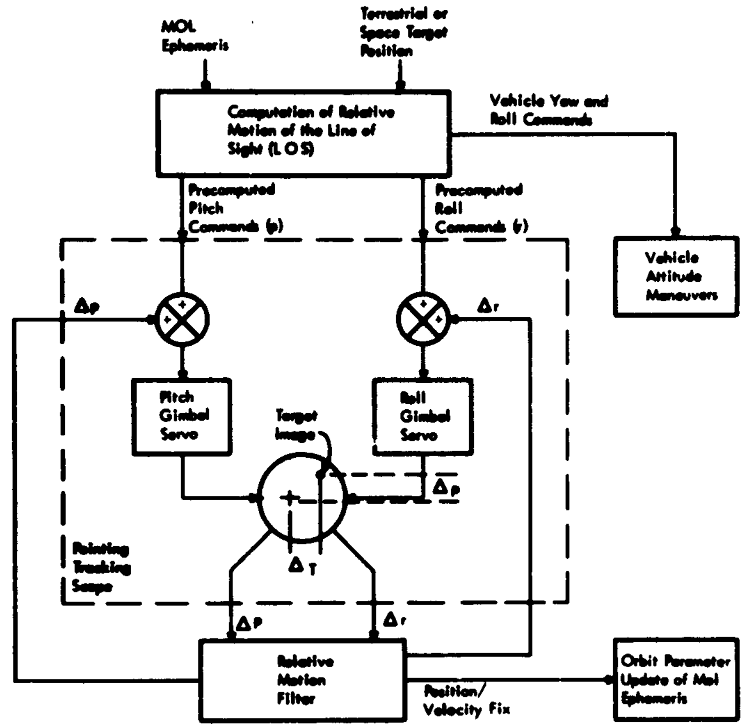


Figure 3-1 Information Flow for Acquisition and Tracking Terrestrial Targets

3.1.1.1.1 Pointing Accuracy and Field of View — The field of view requirements can be derived by considering the navigation and pointing errors associated with MOL and postulating a reasonable design goal that ensures the target is almost always included within the field of view even in the face of these errors.

Let it be assumed that a target area of square dimensions (dxd) is to be photographed. If there are no navigation, altitude or pointing errors, the target will always be included within a square field of view if the side (S) of the square is taken to be equal to the diagonal of the target size.

Figure 3-2 shows that setting $S = \sqrt{2}d$ ensures that a square target is always included for all orientations of the target with respect to the field of view if no errors exist. When errors do exist, they will contribute a circular error of ΔP so that the field of view dimension (S) should now be given by:

$$S = \sqrt{2}d + 2\Delta P$$

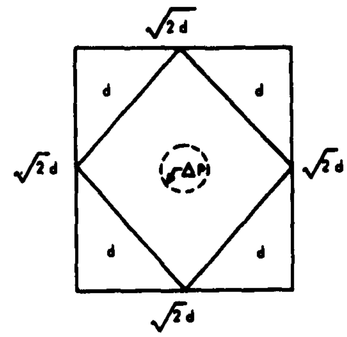


Figure 3-2 Target Characteristics

The error (Δ P) is composed of position, altitude and pointing errors. Figure 3-3 contains a plot of the field of view (S) for the ranges of the parameters shown in Table 3-1. Results from a preliminary study indicate that S is fairly insensitive to orbital altitude but is strongly dependent on target size, elevation angle, and navigation position error.

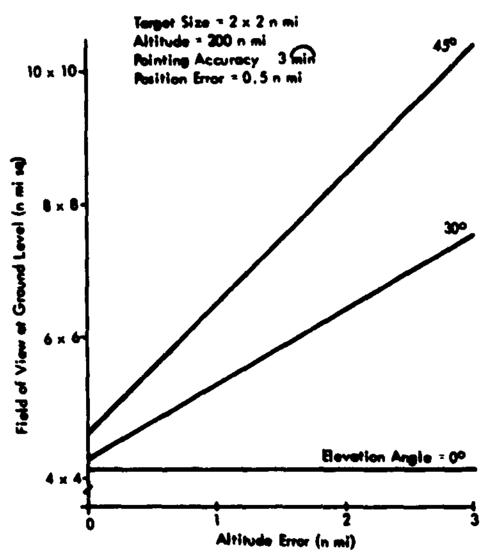


Figure 3-3 Field of View Necessary to Ensure Target is Included

Table 3-1
PARAMETER VALUES USED IN DETERMINING FIELD-OF-VIEW DIMENSION(S)

Parameter	Typical Values	Range
Target Size	2 x 2 n mi sq	1 x 1 n mi sq ---- 4 x 4 n mi sq
Elevation Angle	0^{o}	0^{o} ---- 45^{o}
Pointing Error	3 min	1 min ---- 6 min
Vehicle Altitude	200 n mi	70 n mi ---- 200 n mi
Position Error	5 n mi	0.5 n mi ---- 7 n mi
Altitude Error	1 n mi	0 n mi ---- 3 n mi

It appears that a minimum field of view of 8 n mi square may be required from an altitude of 200 n mi to ensure that the target is included. This figure is based on the assumption that almost all target sizes of interest are contained within a 2 × 2 n mi area. Assuming the worst combination of the errors tabulated in Table 3-1 at an elevation angle of 45 degrees for a 2×2-n mi target and 200 n mi altitude, the minimum field of view becomes 25×25 n mi or 7.5 degrees.

3.1.1.1.2 Image Quality and Nature of Target — Figure 3-4 shows how resolution affects the recognition effectiveness for several types of ground targets. Recognition effectiveness is defined as:

$$RE = (\text{completeness}) \times (\text{efficiency})$$

$$= \frac{(\text{Number of targets located})}{\text{total number of targets available}} \times \frac{(\text{number of targets located})}{\text{number of attempts}}$$

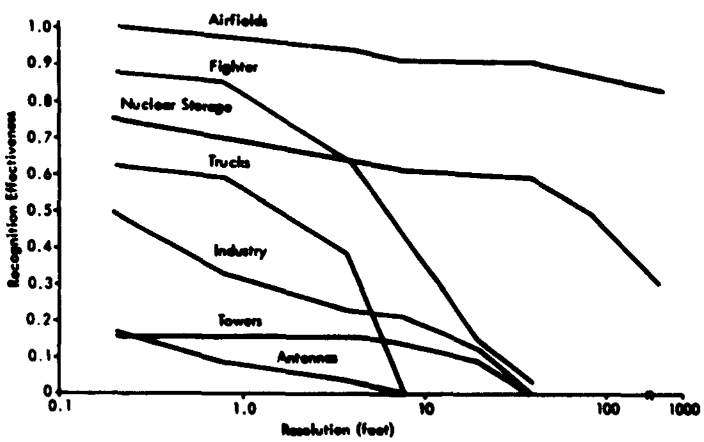


Figure 3-4 Effectiveness as a Function of Resolution for Briefed Targets

It is seen from Figure 3-4 that when resolution is degraded to about 10 feet, several types of targets cease to be easily observed or recognized. Contrast is also important, yet unfortunately uncontrollable to a large extent. Both influence magnification, as discussed more particularly in Section 3.2.

3.1.1.1.3 Observation Time – As shown in Figure 3-5, the time available for viewing and acquisition within tolerable obliquity angles is less then 300 seconds. At smaller obliquities, of order +20 degrees, for which targets are easily recognized and accurate tracking performed, the reduction in viewing time is drastic. The capability of the astronaut to perform under time pressure is discussed in Volume II.

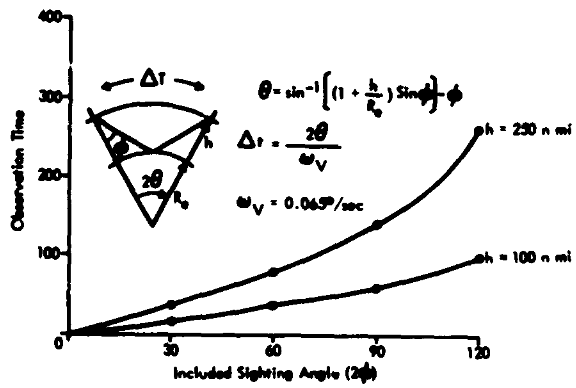


Figure 3-5 Effect of Sighting Angle on Observation Time

3.1.1.1.4 Weather and Illumination – The problems posed by cloud cover can be alleviated by having the astronaut search for the target through breaks in the cloud deck. This requires that the system maintain track of LOS.

The atmosphere, in addition to causing losses in image contrast, introduces the important phenomenon of shimmer or atmospheric trembling, which can strongly affect the resolution, as discussed in more detail in Section 3.2.

In the ground tracking experiment, the illumination of the target varies from the conditions which pertains to a sun angle of 40 degrees through twilight. Image quality is degraded at the lower illuminations due to the exposure times required and the increased dimensions of shadows.

3.1.1.2 Tracking of Ground Targets

Factors that affect the ability to track ground targets are:

- Tracking command signal errors
- Line of sight controller errors
- Tracking techniques
- Magnification (see Section 3.2)
- Resolution of image (see Section 3.2)
- Nature of photo acquisition
- Tracking time
- Man's ability to detect image motion (see Volume II)
- Stabilization errors (see Sections 3.4 and 3.5)
- Weather and illumination

Factors that present significantly different problems from those of acquisition are discussed briefly in the following paragraphs.

3.1.1.2.1 <u>Tracking Command Signal Errors</u> — The LOS velocity and angular acceleration profiles associated with sighting on ground targets are shown in Figures 3-6 and 3-7. Maximum acceleration occurs at $\phi = 30$ degrees, corresponding to least accurate tracking. This suggests that the astronaut's tracking performance be recorded at this angle.

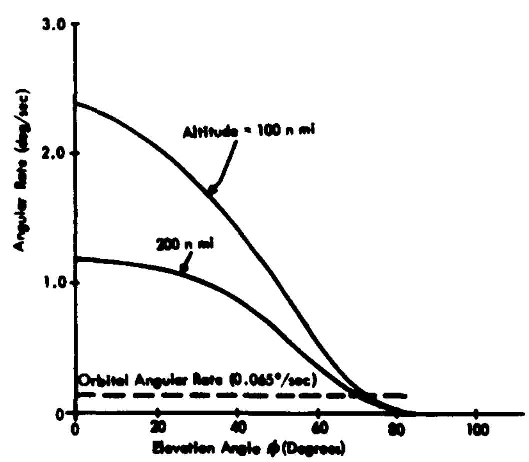


Figure 3-6 Angular Rate Profile for LOS to Ground Targets

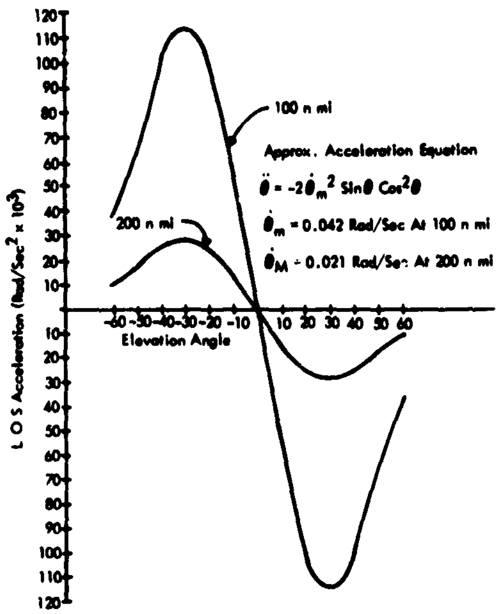
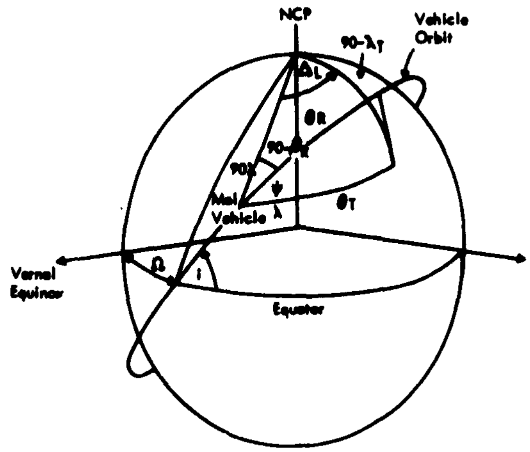


Figure 3-7 Ground Target LOS Acceleration Profile

Figure 3-8 shows the geometry associated with the tracking of a ground target in a geographical coordinate system. Figure 3-9 illustrates the conversion of relative position into sensor pointing angles, (P_r and ψ) relative to the orbit plane.

Before reaching the target area, the MOL's orbital ephemeris is updated by position and/or velocity fixes, either by autonomous landmark sightings or from ground tracking data. After updating, MOL's orientation for ground tracking is computed. The MOL can be oriented in one of two attitudes: (1) orienting the longitudinal axis in the orbital plane, (ψ = 0) maintaining zero roll angle; (2) orienting the longitudinal axis in the orbit plane, and roll MOL to include the target in the PTS scanning plane. Orientation 1 requires PTS motion about two gimbals. In both cases, only one PTS gimbal need be driven hard.

The first orientation may be desirable if more than one target is to be tracked in one pass over a preassigned target area. In fact, the number and spacing of these targets can be treated as a parameter of the experiment which may be varied. Orientation 1 implies minimum expenditure of attitude control propellant.



$$\cos\theta_T = \sin\lambda \sin\lambda_T + \cos\lambda \cos\lambda_T \cos\Delta_L$$

$$\psi = \beta_R - \cos^{-1}\left(\frac{\cos\lambda_T \sin\Delta_L}{\sin\theta_T}\right) \qquad \beta_R = \cos^{-1}\left(\frac{\cos i}{\cos\lambda}\right)$$

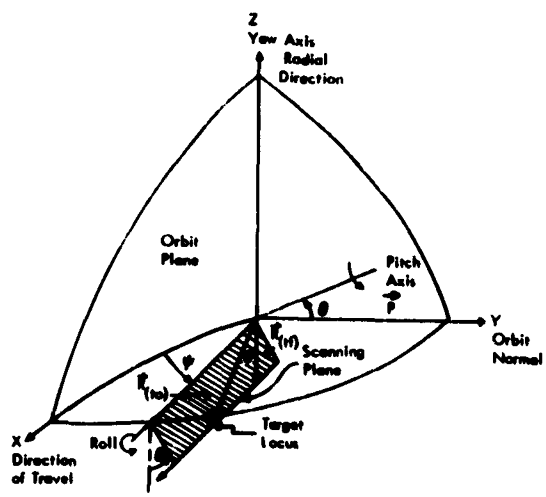
$$\Delta_L = L_T - L + (\omega_o -)t \qquad \omega_o = 0.0729 \text{ mr/sec}$$

$\dot{\Omega}$ = Regression of Lines of Nodes

$$\dot{\theta}_R = \omega_V + (\omega_o + \dot{\Omega}) \cos\lambda \cos\beta$$

$$\dot{\theta}_C = (\omega_o - \dot{\Omega}) \cos\lambda \sin\beta_R$$

Figure 3-8 Computation of Position and Velocity Relative to Target



$$\vec{P} = \frac{\vec{R}_{(to)} \times \vec{R}_{(tf)}}{R_{(to)} \times R_{(tf)}}$$

$$\cos\psi = \vec{X} \cdot (\vec{R} \times \vec{Z})$$

$$\cos\theta = \vec{X} \cdot \vec{P}$$

Figure 3-9 Vehicle-PTS Coordinate System

The implications of multi-target tracking on a single orbit overflight are considerably different than for tracking just one target. In the latter case, once the astronaut acquires the target, he can effectively eliminate most of the static pointing errors (such as those due to navigation, vehicle attitude, and boresight errors). But, his corrections are valid only for the one target, unless additional instruments are included for estimating these errors and the other state vectors contributing to image motion. Multi-target tracking requires star trackers, or an IMU, to keep track of vehicle motion between targets; an orbital ephemeris update may also be necessary. This subject is discussed in more detail in Sections 3.4 and 3.5.

In orientation 2, the relative geometry can be solved in faster-than-real-time to determine the time (t_o) at which the sighting angle (θ) drops below a prescribed maximum obliquity (e.g. 60 degrees). For this time (t_o), a MOL orientation is computed so that MOL is aligned in yaw to be parallel to the precomputed relative velocity vector of the target. The MOL is then aligned in roll so that the PTS scanning plane includes the target relative velocity vector. MOL is then positioned in yaw and roll by the astronaut; the PTS is commanded in pitch for target acquisition at time (t_o). Figure 3-9 shows the pertinent coordinate system. The longitudinal axis is to lie approximately within the orbit plane (ψ = 0). If the target is contained within the orbit plane, the PTS pitch axis will be approximately normal to the orbit plane. The apparent yaw drift angle caused by Earth rotation and oblateness can amount to as much as 3.5 degrees as illustrated in Figure 3-10.

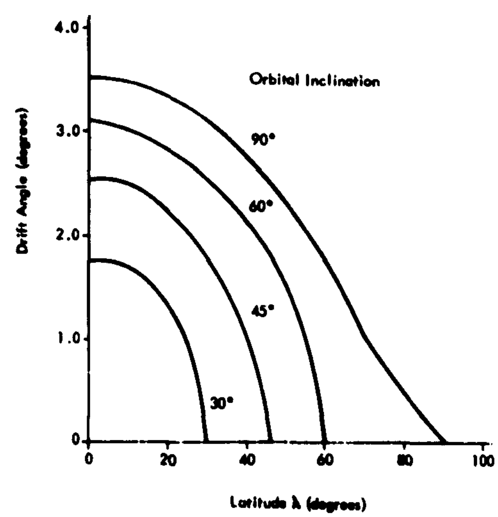


Figure 3-10 Apparent Drift Angle from Orbital Plane Due to Earth Rotation and Oblateness

Thus, if the astronaut uses the PTS to eliminate crossplane drift, he is actually aligning the vehicle's longitudinal axis to ground track, which is not in the orbital plane. The effects of earth rotation and oblateness, however, can be easily accounted for in computing the PTS pointing angles.

3.1.1.2.2 Line of Sight Controller Errors – Only those errors which pertain to orientation 2 are considered in this section. After MOL is aligned in yaw, it is rolled to minimize the PTS roll gimbal excursions. The PTS is commanded to point along the LOS vector $R(t_o)$. At time t_o, precomputed pitch commands cause the PTS to track the point where it "thinks" the target is. This assumed target position is normally in error due to errors in target intelligence or mapping, orbital ephemeris, attitude reference and stabilization, and sensor pointing.

As the LOS becomes more oblique, the apparent image motion of the target increases as a function of its displacement from the computed LOS because image motion can only be compensated at one value of slant range. This motion occurs because image motion must be computed as a function of slant range from the focal plane to a point on the earth's surface. And since the slant range varies across the field of view (FOV), all other points within the field of view will appear to drift either toward or away from the center. This effect becomes more pronounced as the LOS obliquity increases. The magnitude of this drift is shown in Figure 3-11.

3.1.1.2.3 Tracking Techniques – The astronaut can null the image motion on the scope in two ways: (1) by a semi-automatic rate technique in which the astronaut attempts to continually follow the target with his crosshairs; (2) by a discrete technique, wherein the astronaut periodically centers the target under the crosshairs, while the computer records the target travel in scope coordinates. The target is then allowed to drift until the astronaut drives it back under the crosshairs. The procedure is repeated as necessary to arrest target motion. In either case, the apparent best method of arresting the motion is to place a "rate-plus-proportional" control in the hand control loop. This technique allows both position and velocity errors to be nulled out simultaneously. This procedure is similiar to that used in the Wind Memory Point Mode of the AN/ASQ - 38(V) system for the B-52 aircraft, whereby wind information could be updated.

The deviations of the target's image from the crosshairs are processed through a linear "relative motion filter," placed in the PTS gimbal servo feedback loop to arrest the image motion in real time. This filter progressively reduces the target drift to a negligible magnitude, and if it is not used, target drift could probably not be properly arrested for even a

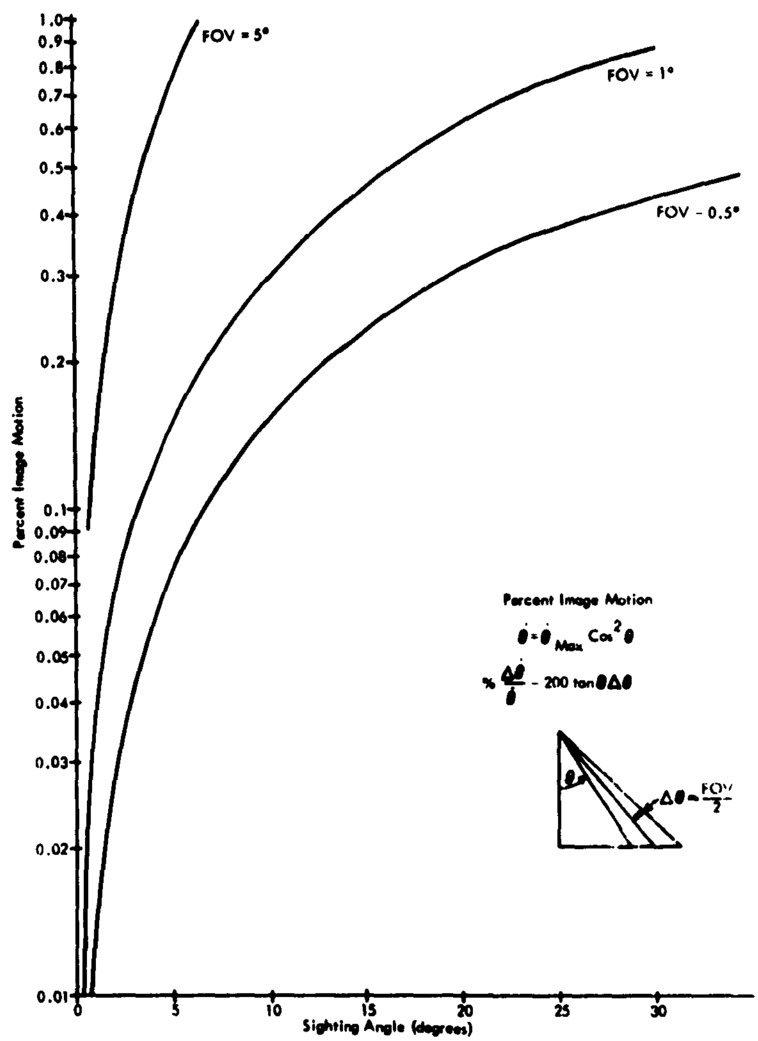


Figure 3-11 Percentage Angular Rate Deviation at Extremities of Field of View (FOV)

short period of time. The relative motion filter could be used to eliminate as many as all 12 state vectors, which cause motion of the line-of-sight. (The state vectors comprise three each of position, velocity, attitude angle, and attitude rate.) In this manner, the relative motion filter allows a navigation position fix update to be accomplished concurrently with the target tracking.

3.1.1.2.4 Nature of Photo Acquisition — Two camera pointing techniques can be employed to measure the amount of image motion compensation accomplished by the astronaut. These are illustrated in Figure 3-12. In the coupled camera technique, the camera, which is slaved to the PTS, always points to the target. The film need not be moved during the exposure, since the image motion is stabilized. This has the additional advantage of eliminating all concern for static errors which the astronaut can effectively remove.

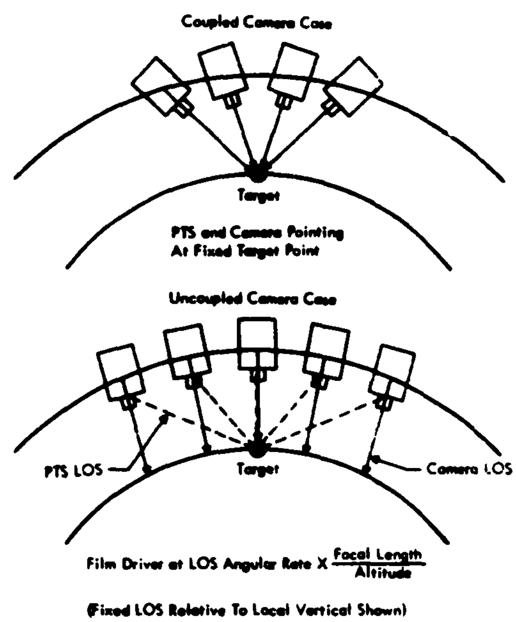


Figure 3-12 Camera Pointing Techniques

Since the uncoupled camera technique may be more suited for the heavier cameras, it may not apply for MOL. In this technique, the camera is pointed in a predetermined orientation at which the photographs will be taken. As PTS tracks the target, the astronaut generates error signals that continually update the film drive for IMC and the orientation of the

heavy camera. As MOL traverses the target, the PTS and the camera come together so that when the picture is taken, PTS and camera look essentially down the same light of sight.

One variation of the uncoupled camera technique consists of acquiring several fixes before traversing the target area and calibrating out the IMC and camera pointing errors prior to target acquisition.

3.1.2 Acquisition and Tracking of Space Targets

The significant differences between space and terrestrial targets are as follows: (1) the relative angular rates associated with space targets vary from near zero to over 30 degrees/second while the rates for ground targets are generally less than 3 degrees/second; (2) the acquisition problems and associated background and illuminations vary widely; and (3) a prediction error volume is associated with space targets, but not with ground targets.

These considerations conspire to make the fly-by the most difficult maneuver in which to acquire and track a space vehicle. The coorbital rendezvous mission is a special case of the fly-by, as pointed out below.

3.1.2.1 Space Target Acquisition

Important factors which affect acquisition of space targets are:

- Target characteristics (see Volume II)
- Illumination of target (see Volume II)
- Range of acquisition
- Observation time
- Field of view/magnification
- Relative motion of LOS
- Target error volume

3.1.2.1.1 Range of Acquisition and Observation Time – The most critical factor in the acquisition process is the severe time constraint associated with the higher relative velocities. This can only be alleviated by extending the lock-on range as far out as possible. This is shown in Figure 3-13, which depicts the variation in encounter time for various angles of closure and acquisition ranges. At the extreme case of right angle crossing ($i = 90$ degrees) there are only 17 seconds left to encounter if the target is acquired at 100 n mi and 170 seconds at 1000 n mi.

3.1.2.1.2 Field of View/Magnification – The desirability of increasing the acquisition range places the following conflicting requirements on the PTS magnification: (1) high magnifications are required to amplify small angular rates against the star background, (2) the high magnifications reduce the field of view and amplify the undesirable stabilization errors, and

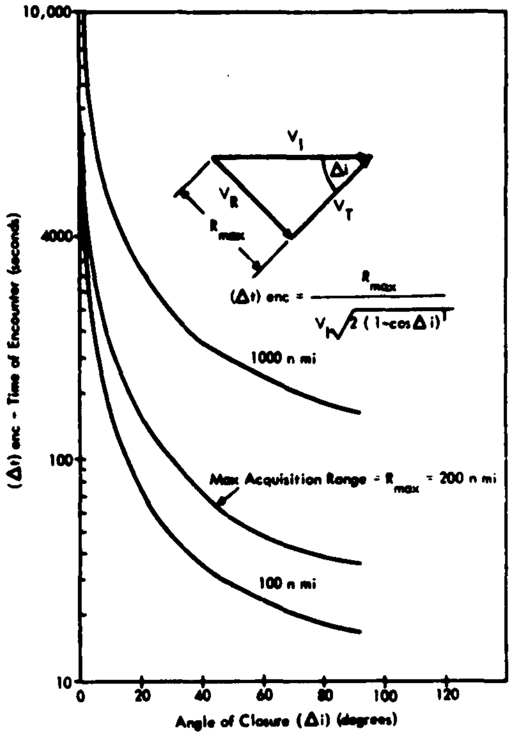
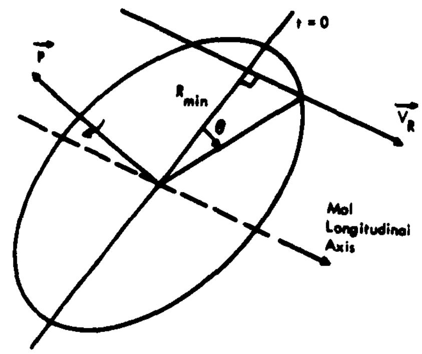


Figure 3-13 Time from Acquisition to Closed Approach for Fly-By Encounter

(3) high magnifications are not required to perceive an illuminated target which is essentially a point source. This discussion is amplified in Volume II.

3.1.2.1.3 Relative Motion of LOS — In the region of closest approach, the relative target-MOL motion is essentially a straight line. The plane formed by the relative velocity vector and the MOL center of mass constitutes the scanning plane in which the PTS will move. This is depicted in Figure 3-14, which is identical to the scanning plane shown in Figure 3-9. Results of the space acquisition simulation indicates that targets with apparent angular rates of 0.12 degree/second were acquired all of the time; the 50 percent acquisition threshold was 0.03 degree/second.

3.1.2.1.4 Target Error Volume Considerations — In planning for the fly-by experiment the ground facilities will transmit the space target ephemeris to the MOL. The ephemeris errors can be represented by an ellipsoid, whose shape and orientation is derived from SPADATS data. The errors in distance of closest approach are derivable from the SPADATS



$$\theta = \tan^{-1}\left(\frac{V_R t}{R_{min}}\right) = \tan^{-1}\left(\frac{t}{\theta_{max}}\right)$$

$$\dot{\theta}_{max} = \frac{V_R}{R_{min}}$$

$$\dot{\theta} = (\dot{\theta}_{max}) \cos^2\theta$$

$$\ddot{\theta} = -2\,(\theta_{max})^2 \sin\theta \cos^3\theta$$

$$R = R_{min} \sec\theta$$

$$R = V_R \sin\theta$$

Figure 3-14 Fly-By Encounter Geometry

data and the angle of closure Δ i: they are presented in Figure 3-15* on a probabilistic basis. For a 99 percent probability of including the target a field of view of 12 degrees is required.

Figure 3-15 shows that for the 3 σ (97 percent) level, fast (Δ i >45 degrees) fly-by encounters should not be attempted where the distance of closest approach is predicted to be less than 10 n mi. This uncertainty produces the undesirable conditions of: (a) vehicle safety problems from a collision view-point and (b) uncertainty as to which direction to roll the MOL vehicle to track the target. For the slower fly-by and coplanar redezvous, these limitations can be relaxed.

Significant factors which affect the ability to track space targets are:

- Image illumination
- Magnification
- Stabilization errors
- Tracking Technique
- Tracking dynamics
- Spinning Targets

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* "Photographic Sensor Subsystem Studies (U)", SSD-TDR-63-395, Volume III, January 1964, Secret.

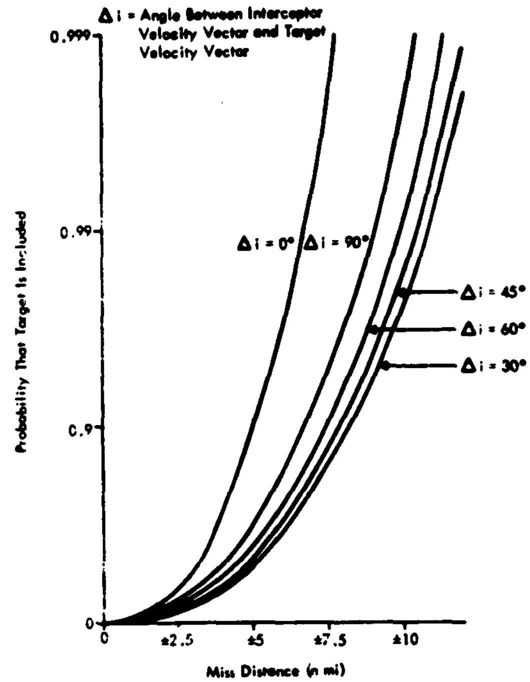

Figure 3-15 Impact of Space Target Error Volume on Prediction of Fly-By Encounter

- Command signal errors
- Maneuverable Targets
- Nature of Photo Acquisition

Several of the comments pertaining to space target acquisition are applicable to the above factors for tracking. Therefore the discussion below is aimed at those factors which present significantly different problems.

3.1.2.2.1 Image Illumination Contrast — Once the space target has been acquired, it will be desirable not to inadvertently lose it because (1) it is approaching the direction of the sun, or (2) it is passing into the umbra region of very small illumination. The general purpose computer (or the ground facilities) can circumvent these problem areas with a subroutine used in planning the experimental fly-by. The extent of this relief can be varied for the purposes of experimentation.

3.1.2.2.2 Tracking Technique — A desirable feature of the PTS is the capability to maintain a constant image slew rate across the scope, independent of magnification and of PTS angular rate. The fast slew rate coupled with a slower tracking rate, should facilitate target tracking by the astronaut.

3.1.2.2.3 Tracking Dynamics – The critical tracking factor is associated with the large LOS accelerations encountered just before the closest approach. Figure 3-16* contains non-dimensional plots of the equations listed in Figure 3-14. Figure 3-17 shows a plot of θ_{max} for various R_{min} and Δ i values. Restricting the values of R_{min} to larger than 10 n mi implies maximum angular rates of about 35 degrees/second.

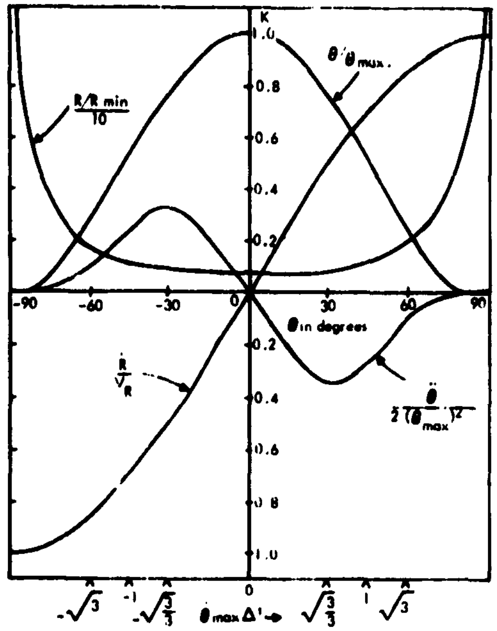

Figure 3-16 Encounter Geometry Dynamics

3.1.2.2.4 Spinning Targets — Another factor to be considered is the peripheral speed of the space targets, which according to the SOW, may be rotating at speeds which result in surface speeds up to 30 fps. This factor will be considered in the tracking servo design for those cases where the target spin is a significant fraction of LOS angular rate.

3.1.2.2.5 Command Signal Errors – The tracking commands that drive the pitch and roll gimbals are generated in a manner identical to that of the ground target sightings, except that the rates and accelerations are accentuated.

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* SSD-TDR-63-395, "Photographic Sensor Subsystem Studies (U)," Volume III, January 1964, Secret.

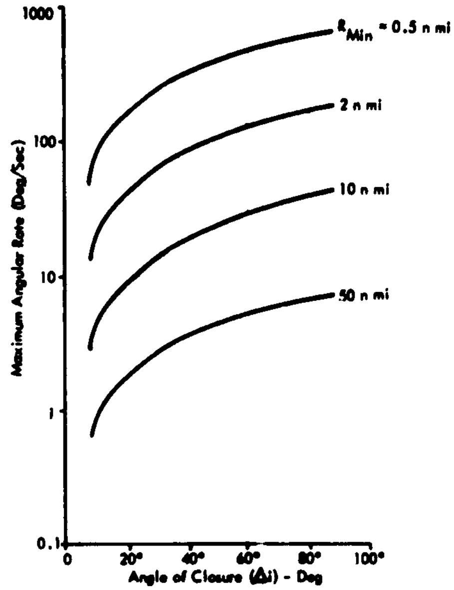

Figure 3-17 Maximum Angular Rates for Tracking of Space Vehicles

Outputs from the tracking system are processed in the relative motion data filter, which can generate relative range to target, angles and angular rates for rendezvous maneuvering, detection of maneuvering targets, and control of camera shutter for taking of photos.

The generation of relative range (R) to the target is accomplished using linear perturbation techniques to update the precomputed relative range. The determination of angles and angular rates can be taken directly from the PTS gimbal servos, or from the digital data filter if smoothing is required.

3.1.2.2.6 Maneuverable Targets — A fairly simple method of detecting maneuverable targets compares the trace of the 3 or 4 sigma covariance matrix to the deviation between the updated and the precomputed trajectory. If the comparison exceeds a prescribed threshold, a discrete is generated indicating that the target was maneuvering.

3.1.2.2.7 Nature of Photo Acquisition — Control of the camera shutter is needed to ensure that photographs are taken at a time and in a manner best suited to assess man's ability to arrest the image motion. This may require the taking of photos within prescribed regions of a phase space, having Δ i, R_{min}, and time as generalized coordinates. The camera shutter can be operated in several modes: (1) automatically preset for taking a certain number frames/second at certain intervals, (2) manual control of start-stop bursts, or (3) manual or automatic taking of individual pictures at discrete times. Each of these modes could be implemented by taking several exposures without moving the film.

3.2 Parametric Analysis for the Optical System

3.2.1 Derived Requirements for the Optical System

This subsection contains a derivation of the design requirements for the optical system in terms of angular resolution, apertures and focal lengths based upon the functional requirements presented in Section 3.2.1.1. The parametric analyses associated with the telescope and recording cameras are then discussed. Included near the end of the subsection is a brief discussion of a low-light-level TV system which could replace the recording cameras for low illumination conditions. The subsection is then summarized with a discussion of the associated image quality analysis.

3.2.1.1 Statement of the Functional Requirements
The requirements specified in Section 2.0 can be restated for the purposes of the optical system.

3.2.1.1.1 P-1 Requirements – The P-1 requirements are as follows:

- Visual-Optical Requirements: The optical instrumentation furnished man, to aid him in arresting image motion, shall be of such quality as to allow him to track to better than 0.2 percent.
- Photo-Optical Requirements: By means of an attached camera, the photo-optical instrumentation shall permit accurate assessment of man's image motion compensation ability.

3.2.1.1.2 P-2 Requirements – The P-2 requirements are the same as those for P-1. (Because of the stated lower priority of P-2 and the fact that the associated optical requirements are less stringent than P-1, the impact of this experiment may well be negligible).

3.2.1.1.3 P-3 Requirements – The optical instrumentation will allow the astronaut to examine ships and surfaced submarines for classification purposes, as well as land-based targets of special interest. Verification photographs will be taken also.

3.2.1.2 Numerical Assumptions
To rephrase the functional requirements in terms of numerical restraints on the optical system parameters, certain assumptions must be made regarding the nominal conditions of the atmospheric optical environment, the optical characteristics of the target, and those optical system characteristics that can readily be specified. The rather arbitrary character of the numerical values quoted below must be kept in mind when reading the subsequent sections of the present discussion.

3.2.1.2.1 Assumptions Regarding the Atmosphere - The following are assumed when the atmosphere is considered:

- The effect of turbulence is ignored
- The background brightness, B, as seen from the satellite is 1000 foot-lamberts
- No assumption is made regarding contrast attenuation in the atmosphere. Instead, the target contrast ratio as seen from the satellite is specified, as described in the following assumptions.

3.2.1.2.2 Assumptions Regarding the Target For P-1 - For the first experiment, the target is assigned the following characteristics:

- The target contrast ratio as seen from the satellite is 1.6:1
- Target shape is circular
- The target has a diameter of 40 feet

These specifications are reasonable for targets such as storage tanks. They are assumed to be acceptable for targets of different shape, but similar dimensions (such as road crossings, roof tops, etc.).

3.2.1.2.3 Assumptions Regarding the Optical System - The following are assumed to be the conditions under which the optical system is operated:

- Satellite Altitude, H = 1000,000 feet
- Satellite Speed, V = 25,000 feet/second
- A maximum line-of-sight zenith angle of 45 degrees
- 6 percent of the available light is transmitted to the Visual Optical System (for the light transmission of the Photo Optical System, see Section 3.2.1.5.1)
- The desired accuracy for photo-optical measurements (see Section 3.2.1.1.1) is p = 0.04 to 0.004 percent of the image motion obtained when observing an earth-bound target with an inertially fixed optical axis.

The range for the desired accuracy, p, was obtained by requiring p to be one-fifth of the expected residual image motion, which was assumed to be between 0.2 and 0.02 percent. The accuracy, p, is meant to represent a three-sigma value, i.e., to represent a maximum possible error.

3.2.1.3 The Optical System Constraints Imposed by P-1

In this section the P-1 functional requirements are rephrased as constraints on the optical system parameters. In the derivation of these constraints, the numerical assumptions listed in Section 3.2.1.2 have been used.

3.2.1.3.1 Visual-Optical System Constraints - In this Section, the Visual-Optical P-1 requirement is discussed. This requirement is interpreted to mean that the astronaut shall have negligible probability for losing his target during the tracking period. Such a situation will prevail when the detection probability of the target image formed by the visual optical system is near unity.

For a sufficiently large visual target diameter (say 6 minutes of arc, to be achieved by an eyepiece of proper magnification), and for a sufficiently large visual background brightness (say, about 4 foot-lamberts), a visual threshold contrast of about 0.02 is needed for a 50% detection probability. Hence, virtually sure detection in a short observation time will occur for a visual threshold contrast of 0.1 (corresponding to a field factor of five). Contrast is here defined as contrast ratio minus unity.

Denoting the target contrast at the periscope by C, it follows from Section 3.2.1.2 that C = 1.6 - 1 = 0.6. Denoting the contrast of the visual target image by C', the preceding discussion imposes the condition that $C' \geq 0.1$. We further observe that C' will be less than C for two reasons: (1) at each of the refracting or reflecting surfaces of the visual-optical system, extraneous light may be scattered into the path of the target light; (2) spreading of the target image as a consequence of lack of resolution of the visual-optical system. We shall ignore the first cause. The second cause is expressed by the following relationship:

$$C' \approx C/\left[1 + \left(2\frac{\theta_{RV}}{\theta_t}\right)^2\right], \qquad (3\text{-}1)$$

where θ_{RV} is the angular resolution of the visual-optical system, and where θ_t is the angular target diameter. Since C = 0.6 and $C' \geq 0.1$ it follows that

$$\theta_{RV} \leq 1.1\ \theta_t . \qquad (3\text{-}2)$$

The angular target diameter in the vertical plane through the line-of-sight is given by

$$\theta_t = \frac{L \cos^2 \theta}{H} \text{ radians}, \qquad (3\text{-}3)$$

where L is the target diameter (assumed to be 40 ft in Section 3.2.1.2.2). Table 3-2 was obtained by combining Equations (3-2) and (3-3).

Table 3-2
VISUAL-OPTICAL RESOLUTION REQUIREMENT FOR P-1

Zenith angle, θ(degrees)	0	30	45
Visual optical resolution, θ_{RV}, at 1.6 contrast ratio.	8.8 sec of arc	6.6 sec of arc	4.4 sec of arc

Next we examine the condition that the visual background brightness, B', as observed through the eyepiece shall be about 4 foot-Lamberts. We note that

$$B' = B \times tr \times \left[\frac{D}{X\,\delta} \right]^2 \qquad (3\text{-}4)$$

where B (= 1000 ft-Lamberts) is the background brightness at the periscope objective, tr is the light transmission of the visual-optical system (= 0.06), D is the aperture diameter of the optical system, δ is the diameter of the eye's entrance pupil (= 0.1 inch) and X is the magnification needed to bring the target diameter up to a visual size of about 6 min of arc. Applying Equation (3-3) and noting that $\theta \leq 45$ degrees from Section 3.2.1.2.3), it follows that $\theta_t \geq 4$ sec of arc. Hence X = 90 is sufficient. Since we require $B' \geq 4$ foot-Lamberts, it follows from Equation (3-4) that $\theta \geq 2.3$ inches. Thus, this value for D, and Table 3-2 express the visual optical conditions for P-1.

The considerations which led to the condtion in Table 3-2 presupposed an isolated circular target approximately 40 feet in diameter. However, with an angular resolution as large as 4.4 sec of arc, it is easily possible, for example, for the individual storage tanks in a closely packed tank farm to become unresolvable.

3.2.1.3.2 Photo-Optical System Constraints – Two types of measurements regarding man's ability to arrest image motion can be foreseen.

One type of measurement may consist of taking two photographs following the tracking period and measuring the shift of the crosshairs. Dividing this by the time interval between the photographs furnishes the residual drift rate and measures the ability of the total system (man plus instrumentation) for arresting image motion. The advantage of this type of measurement is in its relative nature: only the shift of the crosshairs from one photograph to the next need be measured. For example, it is unnecessary to know the precise target tracked by the astronaut.

The second type of measurement is of an absolute nature and, in consequence, will impose stricter constraints on the photo-optical system than the first type. It consists of taking photographs while the astronaut is still tracking, and measuring the distance from the crosshairs to the target the astronaut was tracking. This will furnish a direct measurement of the ability of man to place the crosshairs on the target.

Both types of measurements are discussed below.

3.2.1.3.2.1 Drift Rate Measurement – For this measurement two successive photographs are taken. The crosshair shift relative to the scene photographed is measured and is divided by the time

elapsed between the two photographs to yield the residual drift rate.

The desired maximum error with which the crosshair shift in the image plane is to be measured is determined by the requirement that the error in the drift rate measurement shall be less than p % of the image motion. This would occur when observing an earth-bound target with an inertially fixed optical axis (cf. Section 3.2.1.2.3, where p was assumed to be from 0.04 to 0.004 percent). Hence the desired maximum error in the crosshair shift measurement is given by

$$\text{Desired Maximum Error} = 250\ \text{FxTxp}\ \frac{V \cos^2 \theta}{H}\ \text{microns} \tag{3-5}$$

Here F is the focal length (in inches), T is the time between photographs (in seconds), V and H are in feet/sec and feet respectively, while θ , the zenith angle does not exceed 45 degrees.

$$\text{Hence, Desired Maximum Error} = \begin{cases} 6.3\ \text{FxTxp microns for } \theta = 0^{\circ} \\ 4.7\ \text{FxTxp microns for } \theta = 30^{\circ} \\ 3.1\ \text{FxTxp microns for } \theta = 45^{\circ}. \end{cases} \tag{3-6}$$

Next we discuss the achievable maximum error in the measurement of the crosshair shift. There are three error sources contributing to this measurement:

- The error contributed by the measuring instrument. We assume a three-sigma value of 3 microns for this error. This is reasonable for the accuracy of the satellite - born instrument. For the earth-bound instrument (such as the Mann comparator) the error is likely to be less (probably about 1 micron).
- The error contributed by the graininess of the photographs. The RMS value of the distance between the actual center and the measured center of a circular target is given by

  $$\frac{24\, g\, \bar{D}}{C'\, \gamma}\ \text{microns}$$

  where g is the RMS granularity as published by Eastman Kodak for their films, C' is the target contrast on the photograph, $\bar{D}$ is the mean film density, and γ is the slope of the D-log E curve.
- The error contributed by the photo-interpreter's eyes is assumed to be included in the instrument error of three microns quoted above.

Multiplying Equation (3-7) by three to obtain the maximum rather than the RMS error, one arrives at the following expression for the

achievable maximum error in the measurement of the crosshair shift:

$$\text{Achievable Maximum Error} = \sqrt{2} \cdot \sqrt{3^2 + \left[\frac{72g}{C'\gamma}\right]^2} \text{ microns} \tag{3-8}$$

The square root of two in Equation (3-8) reflects the assumption that the two photographs will be measured separately and will not be superimposed simultaneously.

C' is related to the target contrast C at the periscope objective by a formula similar to Equation (3-1) namely

$$C' \approx C/\left[1 + \left(\frac{2\theta_{RF}}{\theta_t}\right)^2\right], \tag{3-9}$$

where θ_{RF} is the angular resolution of the photo-optical system. According to Section 2.2, C = 1.6 - 1 = 0.6. Assume $g\bar{D}/\gamma = 0.016$ for SO 243 and = 0.031 for SO 226. Table 3-3 was computed from these data using Equations (3-8) and (3-9).

Table 3-3
ACHIEVABLE MAXIMUM ERROR (in microns)

θ_{RF}/θ_t	0.25	0.50	1.00
SO 243	5.4	6.9	14.2
SO 226	7.8	11.4	26.6

Table 3-3 shows a significant increase in error in going from a value of 0.5 for θ_{RF}/θ_t to a value of 1.0. Therefore, we shall require θ_{RF}/θ_t to be 0.5 or less. By computing θ_t from Equation (3-3) the requirements on the photo-optical angular resolution are obtained. They are tabulated in Table 3-4.

Table 3-3 also shows a marked increase in error in going from the slow film SO 243 to the faster film SO 226. Tentatively, it is concluded that SO 243 is, therefore, preferable to SO 226. This conclusion is tentative since image motion (which will be taken into account in Section 3.2.1.5.4) will have a more degrading effect on a slow film such as SO 243 than on a faster film.

Assuming that θ_{RF}/θ_t does not exceed 0.5, it follows from Table 3-3 that the achievable maximum error can be taken as 6.9 microns for SO 243 and as 11.4 microns for SO 226. Hence, in addition to the resolution requirement that θ_{RF}/θ_t shall be 0.5 or less, there is the further P-1 requirement that the desired maximum error, (Equation (3-6)) shall equal the above mentioned achievable maximum error. These two requirements are listed in Table 3-4.

Table 3-4
PHOTO-OPTICAL CONSTRAINTS FOR P-1 DRIFT-RATE MEASUREMENT

Zenith angle θ(degrees)	0	30	45
resolution θ_{RF} for 1.6 contrast ratio.	4 sec of arc	3 sec of arc	2 sec of arc
F x T x p for SO 243	1.1	1.5	2.2
F x T x p for SO 226	1.8	2.4	3.7

Here F is the focal length (in inches), T is the time between photographs (in seconds) and p (in percent) is the allowable drift-rate measurement error in percent of the image motion which would occur with an inertially fixed optical axis.

Two effects have not been considered so far.

- The effect of difference in scales on the two photographs due, for example, to a difference in stretch of the two photographs. Since, on each photograph, the targets can be assumed to be very near to the crosshairs compared with the overall film size, this effect will be ignored.
- The effect of difference in zenith angles of the two photographs. This change in aspect, for example, causes a change in angular target diameter in the vertical plane through the line-of-sight. It is reasonable to demand that this change in target size, when referred to the image plane, shall be no larger than the desired maximum error, Equation (3-5). This requirement leads to the following constraint

  $$\theta \leq 1000 \text{ p cot seconds of arc} \qquad (3\text{-}10)$$

  where θ_t is the angular target diameter and p is as in Equation (3-5). For θ = 45 degrees and p between 0.04 and 0.004 percent, the right-hand side of Equation (3-10) ranges from 40 to 4 seconds of arc. As pointed out earlier, the target characteristics postulated in Section 3.2.1.2.2 lead to a diameter of about 4 seconds of arc when θ = 45 degrees. Thus the target characteristics postulated in Section 3.2.1.2.2 agree in retrospect with the target size limitation imposed by the constraint in Equation (3-10). For this reason, further consideration of the constraint in Equation (3-10) is unnecessary.

3.2.1.3.2.2 Fix-Taking Measurement – For this type of measurement photographs are taken during the tracking period. On each photograph, the angular distance is measured between the crosshairs, and the target tracked by the astronaut. As noted earlier, this type of measurement is of an absolute nature, in contrast to the drift rate measurement, where only the change in crosshair position from one photograph to the next need be measured. Since the fix-taking measurement thus requires the recognition on the photograph of the exact location of the astronaut's target (which in actuality may be something like the corner of a building) it is reasonable to accept the photo-optical resolution as the maximum error to which the target can be located on the photograph. Ignoring instrument error, it follows that photo-optical resolution can be regarded as the maximum error in the fix-taking measurement.

Documentation provided by SSD, as well as computations performed by IBM, indicate that a total fix-taking error (1-sigma error) in the range from 6 to 15 seconds of arc and a tracking time from 20 to 40 seconds suffice to reduce the residual image motion to the order of 0.02 percent of the image motion which would indeed occur for an inertially fixed optical axis.

In addition to these theoretical findings, experimentation with the IBM Earth Sighting Simulator has shown the ability of man to track a target with a fix-taking error (1-sigma error) of about 15 seconds of arc.

Thus it is realistic to consider the range from 6 to 15 seconds of arc as the range of interest for the fix-taking error. Applying the criterion (used in Section 3.2.1.2.3) that the photometric error in the measurement of a quantity shall not exceed one-fifth of the magnitude of that quantity, one arrives at the following constraint for the P-1 fix-taking measurement: the photo-optical resolution shall be from 1.2 to 3 seconds of arc for a target contrast ratio of 1.6:1 at the periscope's objective.

3.2.1.4 The Optical System Constraints Imposed By P-3

The P-3 experiment calls for acquiring and examining sea and land targets of special interest. Specifically, one of its goals is "to examine ships and surfaced submarines for classification purposes". The experiment requires visual examination in real time as well as by means of photographs afterwards.

From available recognition effectiveness data it appears that a ground resolution of about 10 feet is a reasonable choice in that it allows useful recognition of targets such as fighter aircraft; whereas a much smaller resolution seems necessary for recognition of such detail as trucks.

During the course of the study IBM was asked to investigate the impact of a resolution of 5 feet or less for a contrast ratio of 4:1 at the periscope objective for warship classification. This was not interpreted as a requirement for IVSS equipment, rather as another design point in the trade-off analysis.

- A resolution of 10 feet is desired for targets with 1.6:1 contrast ratio at the periscope objective
- For warship classification, a resolution of 5 feet for a contrast ratio of 4:1 at the periscope objective is required.

3.2.1.5 Optical System Requirements in Terms of Focal Length (F) and Aperture Diameter (D)

The optical system constraints derived in the preceding sections are principally formulated in terms of angular resolution for a stated contrast ratio at the periscope objective. In this section the constraints are rephrased in terms of the more convenient design parameters: Focal Length (F) and Aperture Diameter (D).

Since the photo-optical constraints are more stringent than the visual-optical constraints, only the photo-optical case need be considered.

To rephrase the optical system constraints in terms of F and D, additional assumptions over and above those of Section 3.2.1.2 are needed. We proceed to formulate these assumptions in Sections 3.2.1.5.1 through 3.2.1.5.3.

3.2.1.5.1 <u>Assumed Lens Characteristics</u> – Figure 3-18 depicts the modulation transfer functions of three lenses. The ordinate, TL, is the value of the lens transfer function, and the abcissa, U, is a non-dimensional parameter defined by

$$U = \lambda \frac{F}{D} K, \qquad (3\text{-}11)$$

where λ is the wavelength of the light (nominally chosen to be 0.0006 mm) and K is the spatial frequency (in cycles per mm).

The dotted curve in Figure 3-18 depicts the transfer function of an ideal lens, i.e., one which is diffraction-limited. The curves labeled "Lens I" and "Lens II" represent the feasible design of high-performance lenses. Lens II appears to be currently well within the state-of-the-art, while Lens I may necessitate pushing present manufacturing techniques. It is believed that lens performance between these two lens transfer functions can realistically be anticipated.

For Lens I a light transmission of 18 percent through the photo-optical system was assumed. For Lens II a light transmission of 24 percent was postulated. These figures are meant to represent the light transmission effect of the lens, the mirrors, the filters and the beamsplitter.

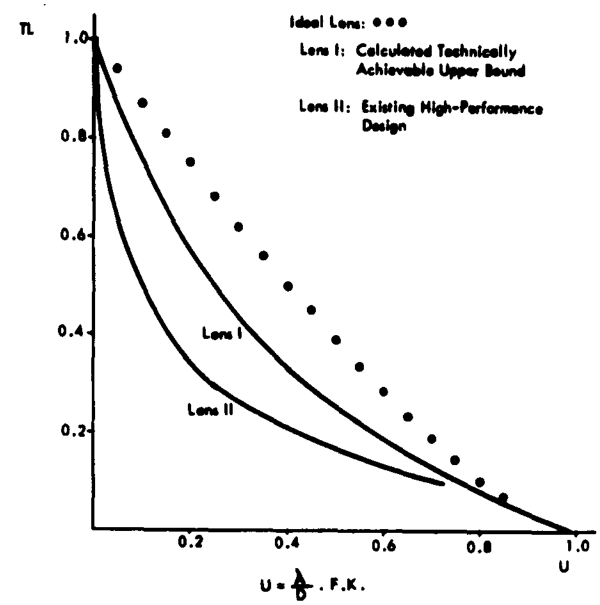

Figure 3-18. Lens Transfer Function

3.2.1.5.2 Assumed Film Characteristics – The Eastman Kodak films SO 243 and SO 226 will be considered. It is evident from the considerations in Section 3.2.1.3.2.1 (particularly from Table 3-4) that faster films would require excessive focal lengths.

In the range of spatial frequencies of interest the film input threshold modulation, FLE, necessary to achieve a film resolution of K cycles/mm is assumed to have a logarithm which is a linear function of the logarithm of K. In other words,

$$\log_{10} \text{FLE} = P.(\log_{10} K) + Q. \qquad (3\text{-}12)$$

The film exposure needed is denoted by E and is measured in meter candles seconds.

The numerical assumptions made are listed in Table 3-5.

Table 3-5
FILM CHARACTERISTICS

Film Type	P	Q	E
SO 243	1.232	-3.631	0.313
SO 226	1.523	-3.902	0.083

3.2.1.5.3 Assumed Uncompensated Image Motion – Uncompensated image motion will cause photographic blur and consequent loss in photo-optical resolution. The uncompensated image motion is assumed to be nearly uniform during the exposure time. High-frequency vibrations (i.e., those whose period is shorter than the exposure time) are ignored.

The angular rate of uncompensated image motion shall be denoted by AM and shall be measured in sec of arc/sec. For preliminary design purposes, values of AM up to 45 sec of arc/sec will be allowed. In fact, the following three specific cases are considered:

$$AM = 0, 30, 45 \text{ sec of arc/sec.}$$

The residual image motion anticipated as man's error contribution was quoted in Section 3.2.1.2.3 to be 0.2% or less of the image motion occurring with an inertially fixed optical axis. A simple computation shows that man's error contribution is thus anticipated to be 10 sec of arc/sec or less. Hence the image motion rates of 30 and 45 sec of arc/sec, proposed for the preliminary design of the photo-optical system, exceed man's maximum anticipated error rate by factors of 3 and 4.5 respectively. These safety factors are, in part, required to accommodate other sources of uncompensated image motion (such as the scanning system's servomechanism). In addition, such safety factors provide a cushion for the inherent arbitrariness of the illumination conditions postulated in Section 3.2.1.2.1. If, for example, the actual illumination conditions require an exposure time twice as long as that predicted on the basis of the assumptions in Section 3.2.1.2.1, then this would imply proposed design image motion rates of only 15 and 22.5 sec of arc/sec. However, these lower rates are still considerably larger than the maximum anticipated human error rate, thus enabling the photo-optical system to accommodate the human error rate even for illumination conditions of much poorer quality.

3.2.1.5.4 Analysis Procedure – The purpose of Section 3.2.1.5 is to translate the photo-optical constraints in terms of constraints on F and D. In the previous sections, these constraints were formulated principally in terms of a specified photo-optical angular resolution, AR, to be achieved for a specified contrast ratio, CR, at the objective of the periscope.

The computational procedure employed for this translation shall now be discussed. We begin by presenting the mathematical relationships between the various optical parameters.

The focal length, F (in inches); the spatial resolution frequency, K (in cycles/mm); and the angular resolution, AR, (in sec of arc) are related by the formula

$$F \times K \times AR = 8000. \qquad (3\text{-}13)$$

The exposure time, t (in seconds); the background brightness, B (in foot-Lamberts); the photo optical system transmission, tr (assumed to be 0.18 for lens I and 0.24 for lens II); and the required film exposure, E (in meter candles sec), are related to F and D in the following manner:

$$E = 2.64 \times B \times tr \quad \left(\frac{D}{F}\right)^2 \times t. \qquad (3\text{-}14)$$

The image motion transfer function, TM, is given by

$$TM = \sin \left[\pi \times AM \times t/AR\right] / \left[\pi \times AM \times t/AR\right], \qquad (3\text{-}15)$$

where AM is in sec of arc/sec as before.

The contrast modulation, CM, is related to the contrast ratio CR by the formula

$$CM = \left[CR - 1 \right] / (CR + 1) \quad . \qquad (3\text{-}16)$$

The contrast modulation, CM; the lens transfer function, TL; the image motion transfer function TM; and the film threshold modulation, FLE, obey the formula

$$CM \times TL \times TM = FLE . \qquad (3\text{-}17)$$

As stated before, FLE can be expressed in terms of K by means of Equation (3-12).

Finally, according to Figure 3-18, the lens transfer function, TL, is a known function of the nondimensional parameter $U = \lambda \times K \times (F/D)$. that is

$$TL = \text{function of } \left(\lambda \times K \times (F/D)\right) \qquad (3\text{-}18)$$

Of the quantities appearing in Equations (3-12) through (3-18), the following are assigned specific numerical values by the assumptions made in previous sections:

- B is assumed in Section 3.2.1.2.1
- λ and tr are assumed in Section 3.2.1.5.1
- P, Q and E are assumed in Section 3.2.1.5.2
- AM is assumed in Section 3.2.1.5.3

This leaves the following ten parameters still unspecified:

$$AR,\ CR,\ F,\ D,\ K,\ t,\ CM,\ TM,\ TL,\ \text{and } FLE. \qquad (3\text{-}19)$$

Since these ten parameters satisfy Equations (3-12) through (3-18), three of them can be freely specified, and this will then determine the numerical values of all ten parameters.

Now consider a photo-optical constraint that requires the angular resolution, AR, to have a specified value for a specified contrast ratio, CR, at the objective of the periscope. The constraint thus assigns specific numerical values to the first two of the ten parameters (3-19). This

for AM = 45 sec of arc/sec in Figure 3-19, for example, represents an optical system with an angular resolution of better than 2.2 sec of arc for a contrast ratio of 1.6 and for image motion of 45 sec of arc/sec.

One feature in Figure 3-19 merits special mention: the minimum for D shown by the curves for non-zero image motion. To explain this feature, note that AR is prescribed by the constraint. Hence, from Equation (3-13) it follows that K will be large when F is small. In fact, there will be a value below which F cannot fall and at which K will equal the maximum resolution frequency that the film can support at the contrast ratio required by the constraint. For this minimum value of F, all available system resolution is taken up by the film, and none is left for the lens which, therefore, must have an infinite diameter. In other words, the curve has a vertical asymptote and must show initially a decreasing value of D as F is increased further and further away from its minimum.

When AM = 0, i.e., when the curve represents the static case, the curve will keep showing a decreasing value of D as F grows larger, because, as F increases, the required system resolution frequency, K, decreases; and the film will need less and less contrast to record it. This allows for an increasing contrast loss in the lens and, therefore, permits the lens diameter to decrease. For very large values of F, the system will be substantially lens-limited, i.e., the required angular resolution, AR, will be nearly completely taken up by the lens, resulting in a limiting lens diameter of 4.8/AR inches. Hence the curve with AM = 0 will have a horizontal asymptote at this value for D (which amounts to 2.2 inches for Figure 3-19).

Whereas the duration, t, of the film exposure will in no way affect the system performance in the static case (AM = 0), this is no longer true for the dynamic case (AM $\neq$ 0). In fact, it follows from Equation (3-15) that TM is zero, and that there will be no transmission at the frequency, K, whenever t = AR/AM. Thus in any situation in which image motion occurs, the exposure time, t, will have an upper limit above which the system performance will be severely degraded. Hence in view of Equation (3-14), there will be an upper limit, β, for the system f-number F/D. Hence, $D \geq F/\beta$, and D must eventually increase with increasing values of F. This implies that any curve for which AM $\neq$ 0 must show a minimum value of D and will possess an oblique asymptote the slope of which is the reciprocal of the limiting value of the system f-number.

3.2.1.5.5 Summary of P-1 and P-3 Photo-Optical Requirements – The P-1 requirements for the drift-rate measurements are listed in Table 3.2-3, Section 3.2.1.3.2.1. Table 3-4 shows that the requirements

become more severe as the zenith angle, θ, is increased. As a practical compromise, IBM will establish as a minimum that the requirements for the zenith angle θ = 30 degrees be satisfied. Thus, an angular resolution of 3 sec of arc or less for a contrast ratio of 1.6 at the objective of the periscope will be required, and FxTxp must be at least 1.5 if SO #243 is used and 2.4 if SO #226 is used.

The P-1 requirements for the fix-taking measurements were stated to be an angular resolution of 1.2 to 3 seconds of arc at a contrast ratio of 1.6 (Section 3.2.1.3.2.2).

Combining both sets of requirements gives the following P-1 photo-optical requirements:

- angular resolution: 3 to 1.2 seconds of arc for a contrast ratio of 1.6 at the objective of the periscope
- FxTxp must be at least 1.5 if SO #243 is used and
- FxTxp must be at least 2.4 if SO #226 is used

The P-3 requirements were listed in Section 3.2.1.4 in terms of required ground resolution. Assuming nadir viewing only, and a satellite altitude, H, of 1,000,000 feet (i.e., H$\approx$ 160 nm), the P-3 requirements can be rephrased in terms of angular resolution as follows:

- For a contrast ratio of 1.6 at the objective of the periscope, the resolution shall be 2 seconds of arc.
- For a contrast ratio of 4 at the objective of the periscope, the resolution shall be 1 seconds of arc (warship classification)

3.2.1.5.6 <u>P-1 and P-3 Photo-Optical Requirements Formulated in Terms Of F and D</u> - To convert the P-1 and P-3 requirements stated in the preceding section to requirements in terms of focal length, F, and aperture diameter, D, a number of curves of D versus F were calculated using the analysis procedure discussed in Section 3.2.1.5.4. The results are presented in Figures 3-19 through 3-32. Each of the following lens-film combinations: lens I: SO #243, lens II: SO #243, lens I:SO #226, and lens II:SO #226 was computed for each of the combinations of angular resolution, AR, and contrast ratio, CR, at the periscope objective shown in Table 3-6.

Table 3-6
COMBINATIONS OF ANGULAR RESOLUTION AND CONTRAST RATIO

AR (sec of arc)	2.2	3.0	1.0	1.33	1.67
CR	1.6	1.6	4.0	4.0	4.0

leaves eight parameters satisfying only seven equations. Hence, one parameter (F for example) can be arbitrarily selected. The remaining seven parameters can then be found by solving Equations (3-12) through (3-18). In particular, after specifying F, the aperture diameter, D, can be calculated. When D is plotted as the ordinate against F as the abcissa, a curve is obtained representing those optical systems which just satisfy the constraint. The choice of F and D for representing the optical system is convenient for several reasons. First, parameters F and D are the conventional parameters used to describe the optical characteristics of an optical system and, the remaining six parameters are readily computed from F and D using Equations (3-12) through (3-17). Second, the parameters F and D provide effective indicators for the physical dimensions which the satellite must accommodate.

Figure 3-19 provides an example of such curves of D versus F. Here AR = 2.2 sec of arc, CR = 1.6, and AM is 0, 30, and 45 sec of arc/sec. All points above one such curve more than satisfy the constraint for the stated uncompensated image motion. That is, any point above the curve Without exception, every combination involving SO #226 required about the same value of D, but a substantially larger value of F than its counterpart with SO #243. This can be seen by comparing the following figures:

- Figure 3.2-12 and Figure 3-19
- Figure 3.2-13 and Figure 3-20
- Figure 3.2-14 and Figure 3-21
- Figure 3.2-15 and Figure 3-22

For this reason, SO #243 must be preferred over SO #226. This conclusion is reinforced by the same conclusion drawn in Section 3.2.3.3.2.1 apropos of Table 3-3. Henceforth, only SO #243 will be considered, and SO #226 will be ignored.

Figures 3-19, 3-20, 3-21, and 3-22 are useful for examining the first part of the P-1 photo-optical requirements, which demand a resolution of 3 sec of arc to 1.2 sec of arc for a contrast ratio of 1.6 at the periscope objective. It is reasonable to require that the resolution of 3 sec of arc be attained with the lower bound design represented by lens II. Using this criterion, it is seen from Figure 3-22 that D $\approx$ 6 inches and F $\approx$ 36 inches. This leaves the requirement of 1.2 sec of arc at a 1.6 contrast ratio. This requirement is far more severe than the 3 sec of arc resolution considered above. In fact, it is even more severe than the P-3, requirement of 1 sec of arc resolution at a contrast ratio of 4. The effect of the latter requirement on F and D can be ascertained from Figures 3-23 and 3-26. As a compromise, IBM will require a resolution of 2.2

sec of arc (which is about midway between 3 and 1.2 sec of arc) for a contrast ratio of 1.6. Referring to Figures 3-19 and 3-21, it follows that D $\approx$ 7 inches and F $\approx$ 36 inches are needed for lens I design and that D $\approx$ 8 inches, F $\approx$ 40 inches for lens II design (allowing for the latter case a maximum image motion of only 30 sec of arc/sec). As the quality of fabrication will probably lie somewhere between the lens I and lens II design, the P-1 photo-optical requirements can be rephrased as

D $\approx$ 8 inches and F $\approx$ 36 inches.

To complete the P-1 requirements, the FxTxp requirements must still be considered. These require FxTxp to be at least 1.5 (according to Table 3.4 Section 3.2.1.3.2.1, FxTxp is to be at least 1.1 when θ = 0 degrees, 1.5 when θ = 30 degrees, and 2.2 when θ =45 degrees). With F = 36 inches and p = 0.04 to 0.004 percent, this leads to the following:

- T = 0.8 to 7.6 sec for θ = 0 degrees
- T = 1.0 to 10 sec for θ = 30 degrees
- T = 1.5 to 15 sec for θ = 45 degrees.

The time, T, allowed between photographs for drift rate measurement is influenced by various considerations such as build-up of servomechanical error (in the case where the human operator is not permitted to aid tracking between photographs) and difficulty in comparing photographs due to differences in aspect and contrast. It would appear that values of T in the range from 5 to 10 seconds are allowable. Hence, the conditions on T can probably be completely satisfied for θ up to 30 degrees and at least partially for θ as large as 45 degrees.

The P-3 photo-optical requirements of 2 sec of arc for a 1.6 contrast ratio can be seen in Figures 3-19 and 3-21 and leads to the choice of D $\approx$ 8 inches and F $\approx$ 36 inches as before.

The second of the P-3 requirements, (warship classification) can be examined in Figures 3-23 and 3-26. Lens I design will require D $\approx$ 12 inches and F $\approx$ 45 inches, and lens II design will require D $\approx$ 14 inches and F $\approx$ 60 inches. Thus, the P-3 photo-optical requirements can be rephrased in terms of D and F as follows:

- For the first requirement, D $\approx$ 8 inches and F $\approx$ 36 inches appears to be marginally adequate.
- For the second requirement, D $\approx$ 12 to 14 inches and 45 to 60 inches.

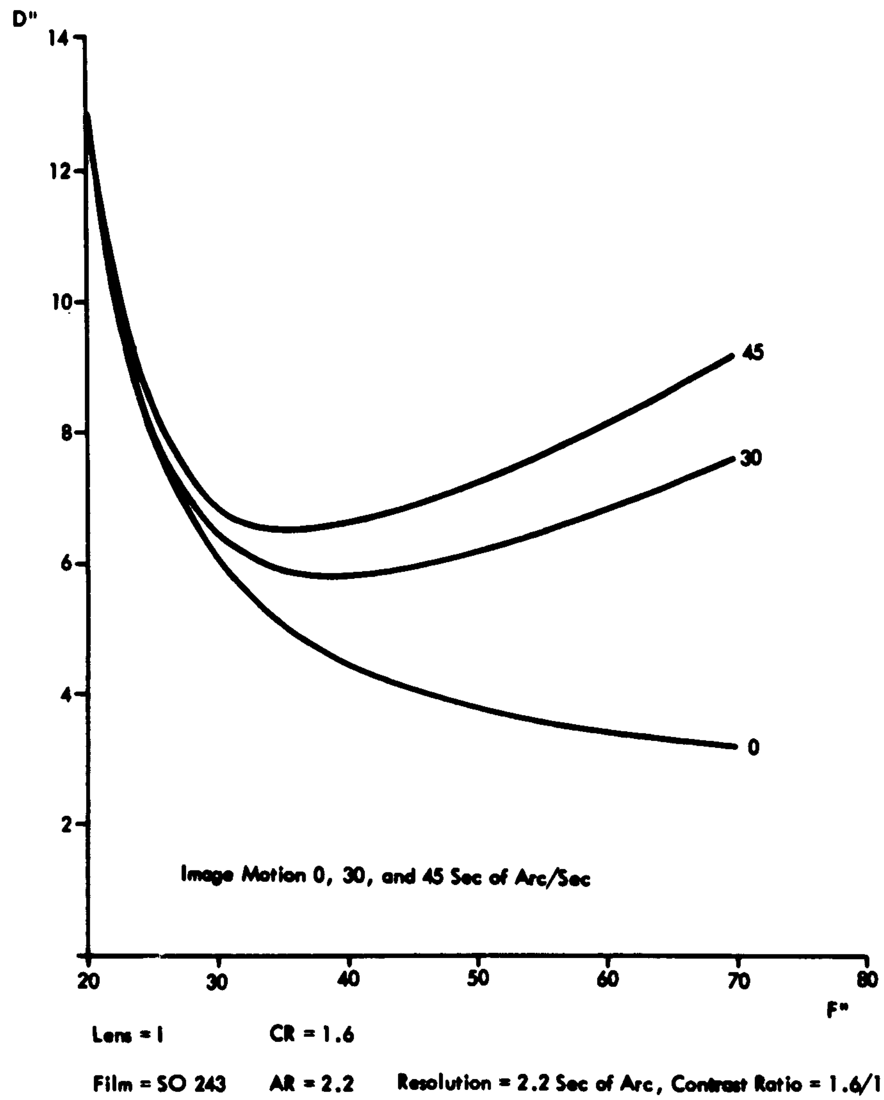

Figure 3-19. Aperture (D) vs Focal Length (F) for Resolution of 2.2 $\widehat{\text{Sec}}$, Lens I

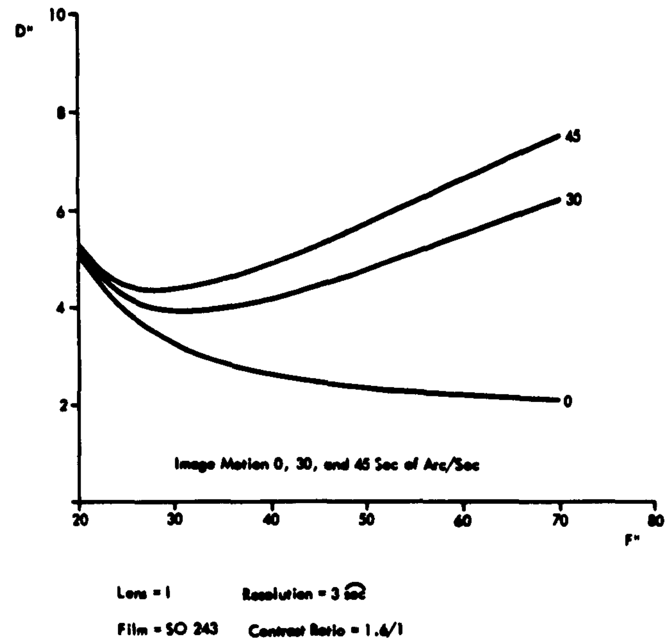

Figure 3-20. Aperture (D) vs Focal Length (F) for Resolution of 3 Sec, Lens I

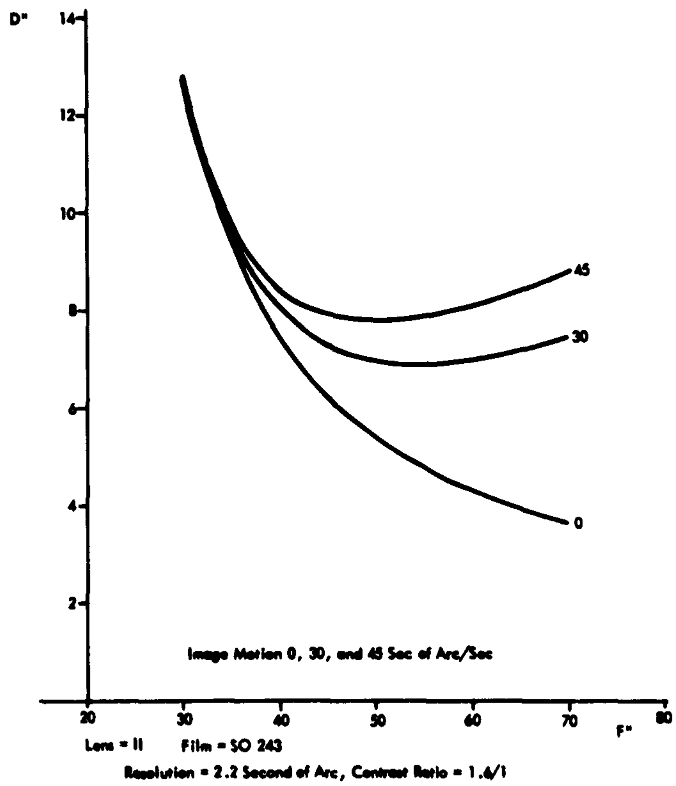

Figure 3-21. Aperture (D) vs Focal Length (F) for Resolution of 2.2 Sec, Lens II

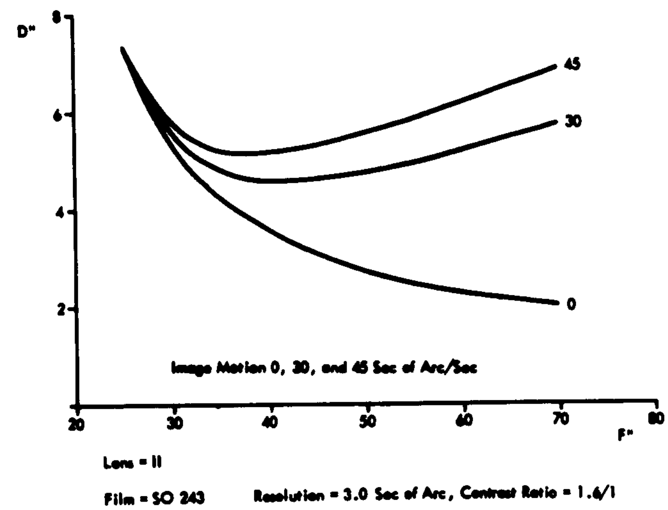

Figure 3-22. Aperture (D) vs Focal Length (F) for Resolution of 3 $\widehat{\text{Sec}}$, Lens II

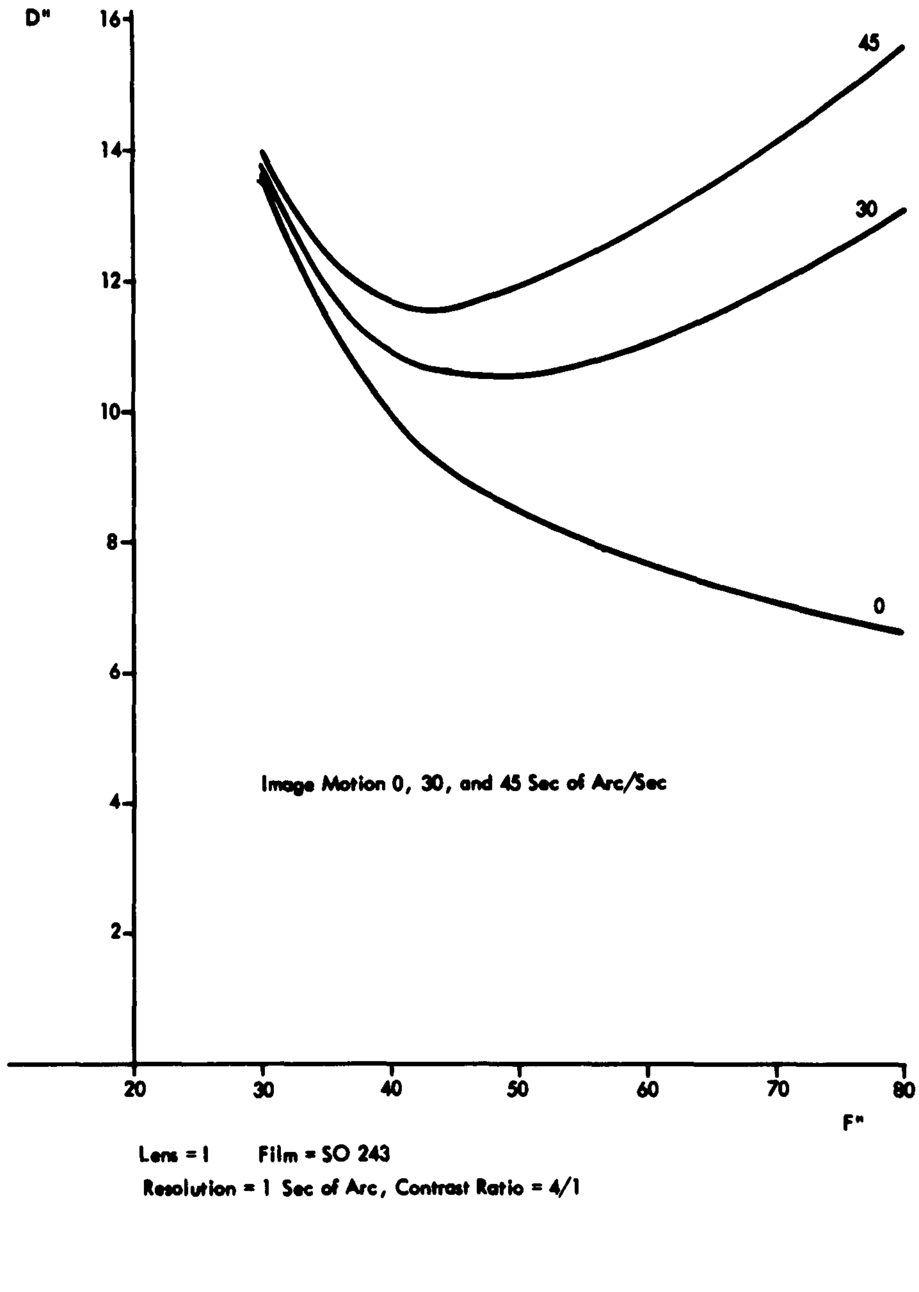

Figure 3-23. Aperture (D) vs Focal Length (F) for Resolution of 1 $\widehat{\text{Sec}}$, Lens I, Contrast Ratio of 4/1

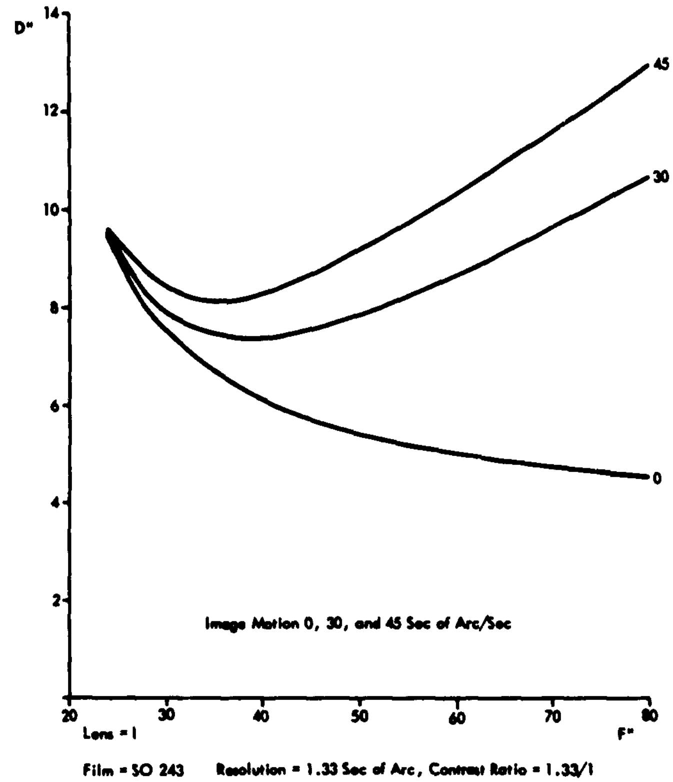

Figure 3-24. Aperture (D) vs Focal Length (F) for Resolution of 1.33 $\widehat{\text{Sec}}$, Lens I, Contrast Ratio of 1.33/1

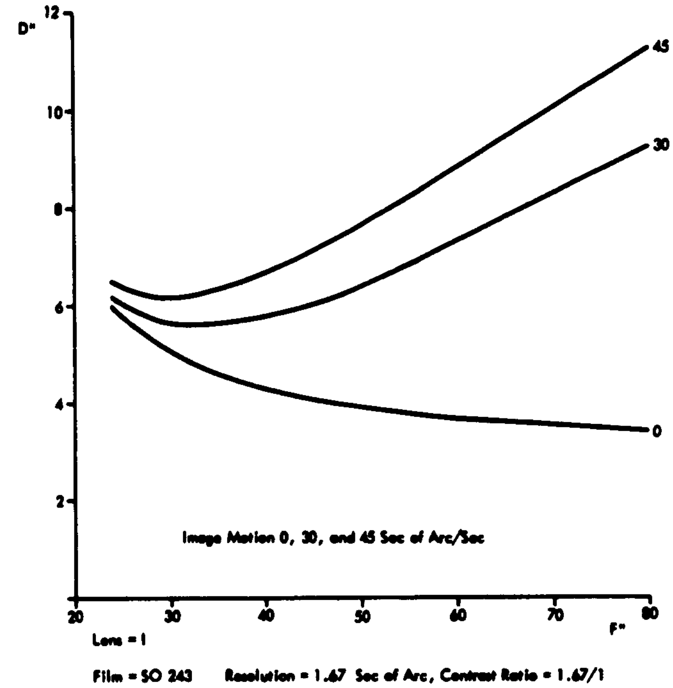

Figure 3-25. Aperture (D) vs Focal Length (F) for Resolution of 1.67 $\widehat{\text{Sec}}$, Lens I, Contrast Ratio of 1.67/1

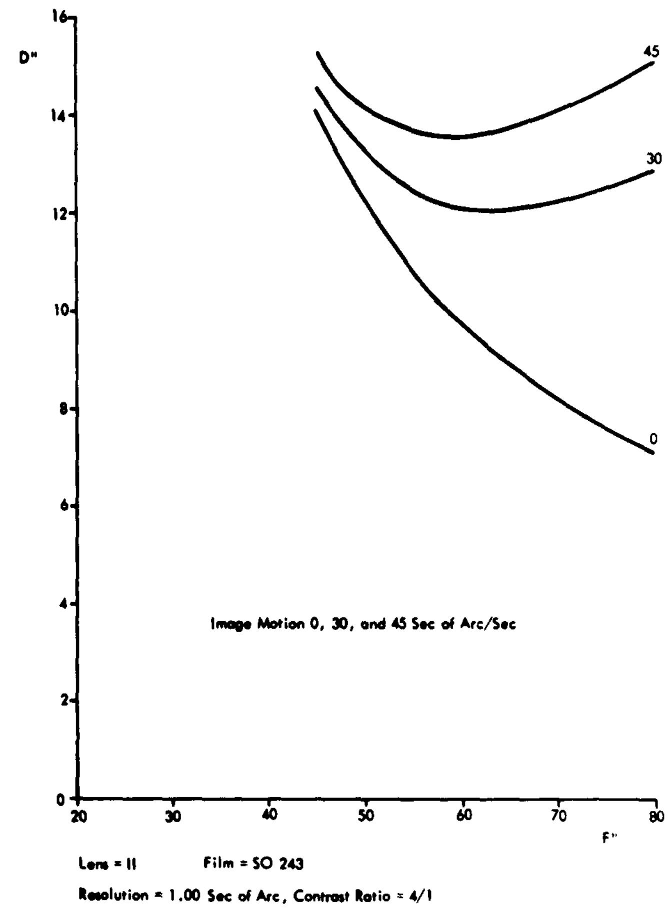

Figure 3-26. Aperture (D) vs Focal Length (F) for Resolution of 1 Sec, Lens II, Contrast Ratio of 4/1

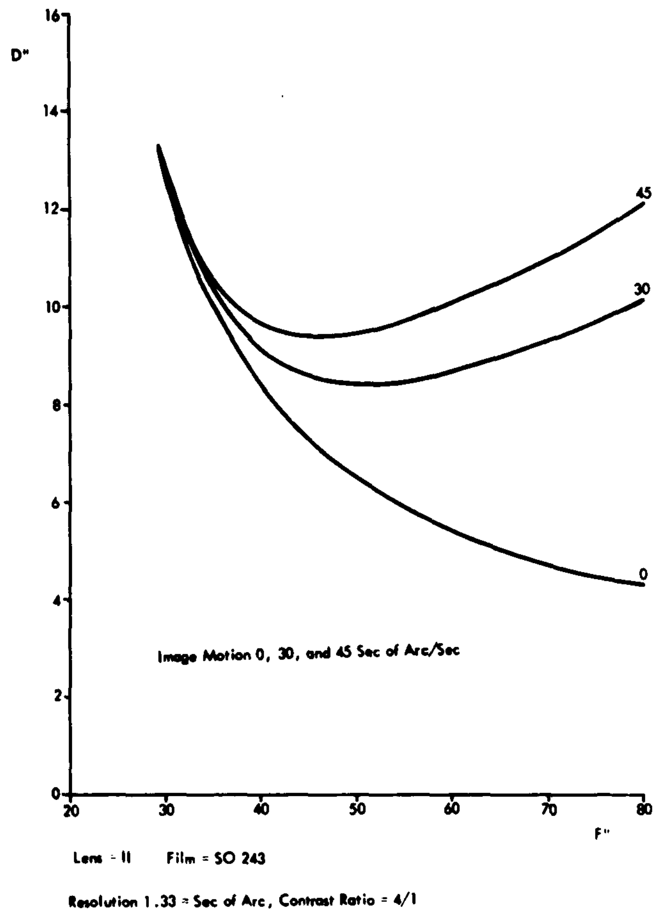

Figure 3-27. Aperture (D) vs Focal Length (F) for Resolution of 1.33 $\widehat{\text{Sec}}$, Lens II, Contrast Ratio of 4/1

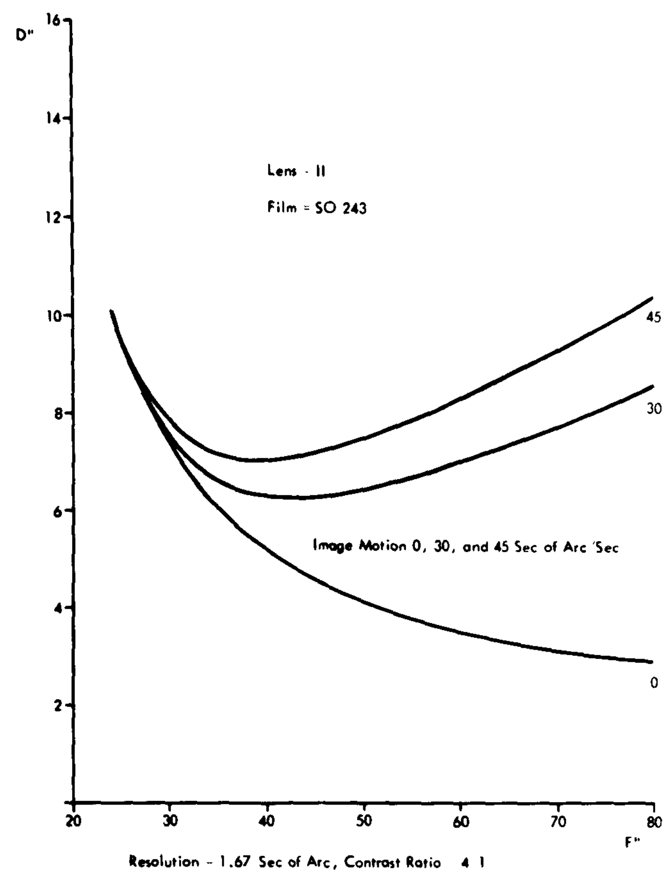

Figure 3-28. Aperture (D) vs Focal Length (F) for Resolution of 1.67 $\widehat{\text{Sec}}$. Lens II. Contrast Ratio of 4/1

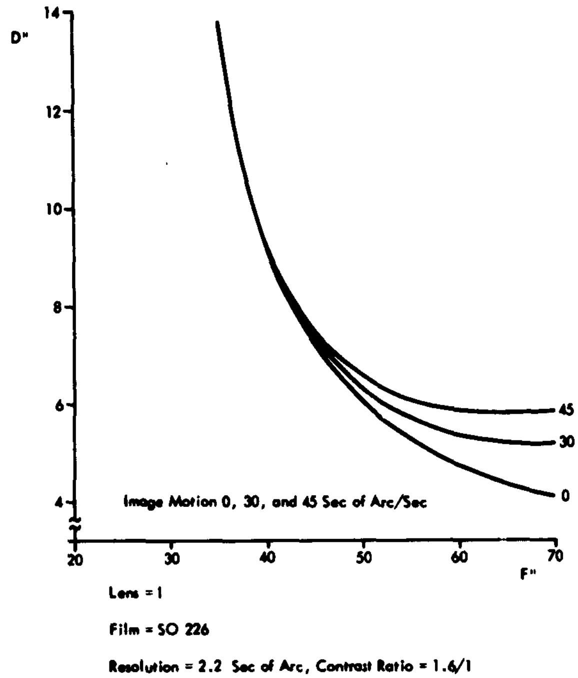

Figure 3-29. Aperture (D) vs Focal Length (F) for Resolution of 2.2 $\widehat{\text{Sec}}$, Lens I, Contrast Ratio of 1.6/1, SO 226 Film

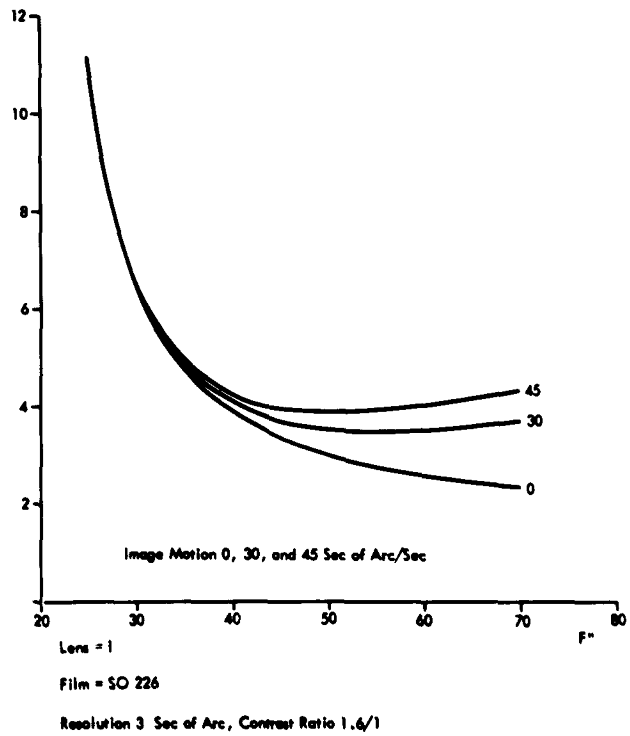

Figure 3-30. Aperture (D) vs Focal Length (F) for Resolution of 3 $\widehat{\text{Sec}}$, Lens I, Contrast Ratio of 1.6/1, SO 226 Film

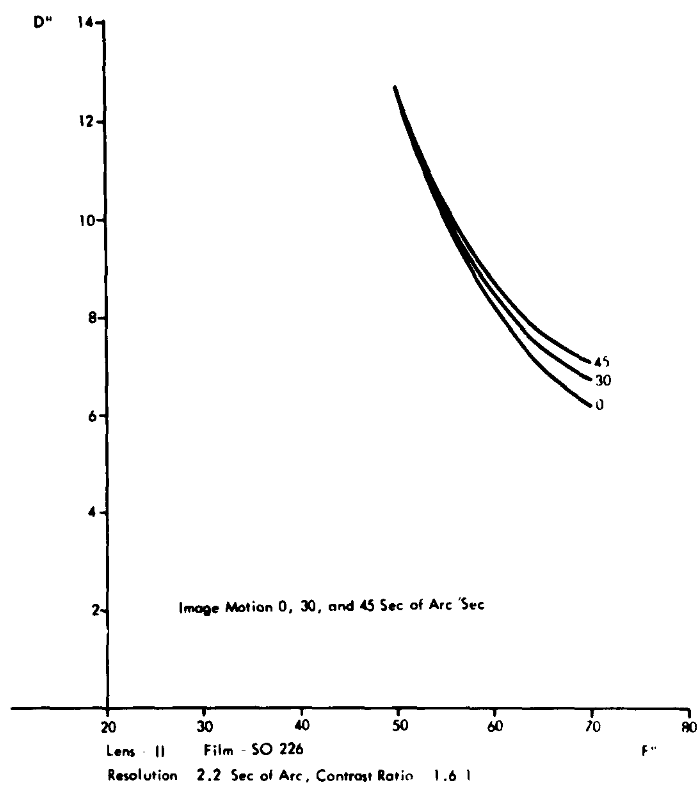

Figure 3-31. Aperture (D) vs Focal Length (F) for Resolution of 2.2 Sec, Lens II, Contrast Ratio of 1.6/1, SO 226 Film

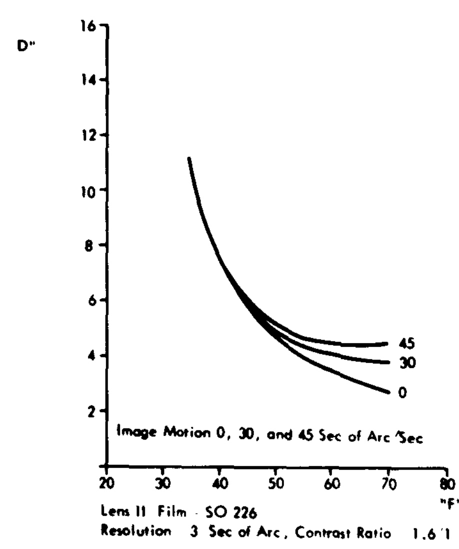

Figure 3-32. Aperture (D) vs Focal Length (F) for Resolution of 3 Sec, Lens II, Contrast Ratio of 1.6/1, SO 226 Film

3.2.2 Pointing and Tracking Scope Optical Configuration

3.2.2.1 Design Criteria

The PTS optical configuration design criteria consist of the following:

- The scanning system must provide near hemispherical coverage with servo-gimballed optics and digital encoders providing accurate angle and angular rate data of the target line-of-sight
- The field of view must be wide enough so that the target image can be reasonably acquired
- The relative aperture must be high enough to see and record the image under the lighting and atmospheric conditions specified in the Statement of Work.
- The physical aperture must be large enough to resolve the detail desired
- The focal length must be long enough to have sufficient detail appear in the final image.

3.2.2.2 Interrelation of Parameters

Figure 3-33 depicts the complex interrelation of optical design parameters and how they are derived from the requirements relating to: (1) target recognition, (2) field of view, (3) scan requirements, and (4) experiment evaluation requirements.

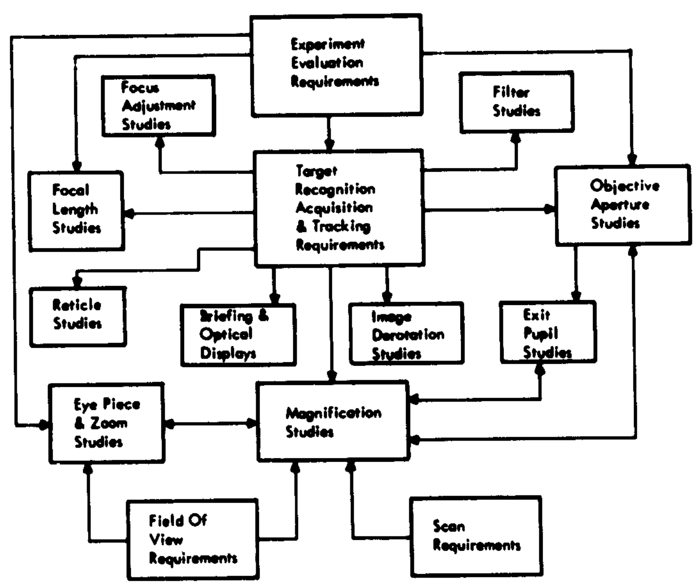

Figure 3-33 Interrelation of Optical Parameters

3.2.2.3 Optical System Parameters

The key features of the PTS optical configuration are discussed in the following paragraphs.

3.2.2.3.1 Magnification - This optical parameter is perhaps the most important to be defined since it is strongly related to almost all of the other parameters. Human factor studies and simulation results dictate the magnification ranges be compatible with the accomplishment of the experimental objectives. For high magnifications certain effects were studied to ensure that the objectives are met. These included: image motion due to imperfect tracking, instrument vibrations and vehicle movements, reductions in image brightness and contrast, reduction in real field, and exit pupil size. Figures 3-34 and 3-35 depict the relationship of real field angle, magnification, and apparent field angle.

The best values of system magnification and corresponding field of view for target acquisition will, in general, not be the preferred values for tracking the target after acquisition; still other values will be indicated for detailed examination of a well tracked target about the time of its closest approach. Thus, a variety of system configurations may be desirable within the span of one observation, lasting perhaps one or two minutes. During the observation, it is desirable to minimize distractions to the observer, who will concentrate on his tracking and observation tasks, and not be concerned with further instrumental considerations.

3.2.2.3.2 Field of View - In the scanning mode when acquiring ground, sea, or space targets, it is advantageous to have low magnification for slow image velocity and to have a fairly wide field angle for ease in locating the target. Figure 3-36 shows the ground coverage as a function of range and real field angle. The coverage along the line of sight increases as the secant of the elevation angle (angle between local vertical and line of sight). The increase in ground coverage is shown in Figure 3-37.

3.2.2.3.3 Objective - The physical aperture of the recommended objective must be kept small to minimize the mass of the associated scanning optics. To this end, only systems of known excellence of design and fabrication should be considered. The preferred optics are determined by analytical system studies; they are selected on the basis of their ability to satisfactorily image targets of the specified brightness, contrast and size.

The technological achievements of the last decade in sophisticated instrumentation delivery into orbital altitudes has precipatated requirements for unusually high performance photographic objectives. The

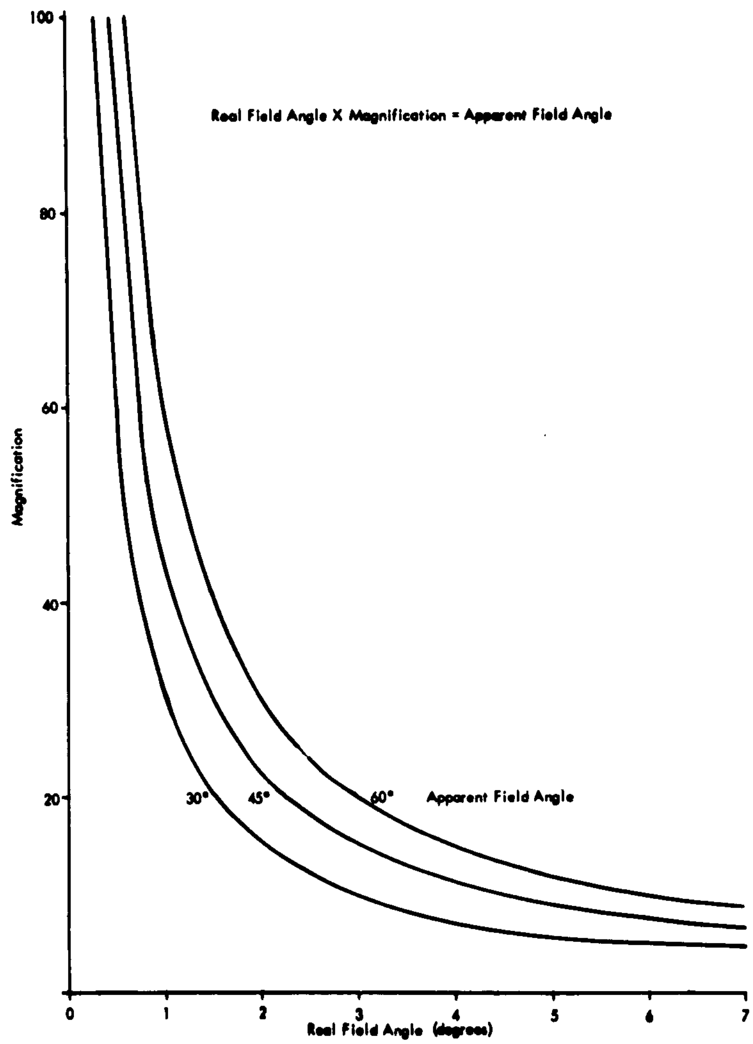

Figure 3-34. Magnification vs Real Field Angle vs Apparent Field Angle (High Magnification)

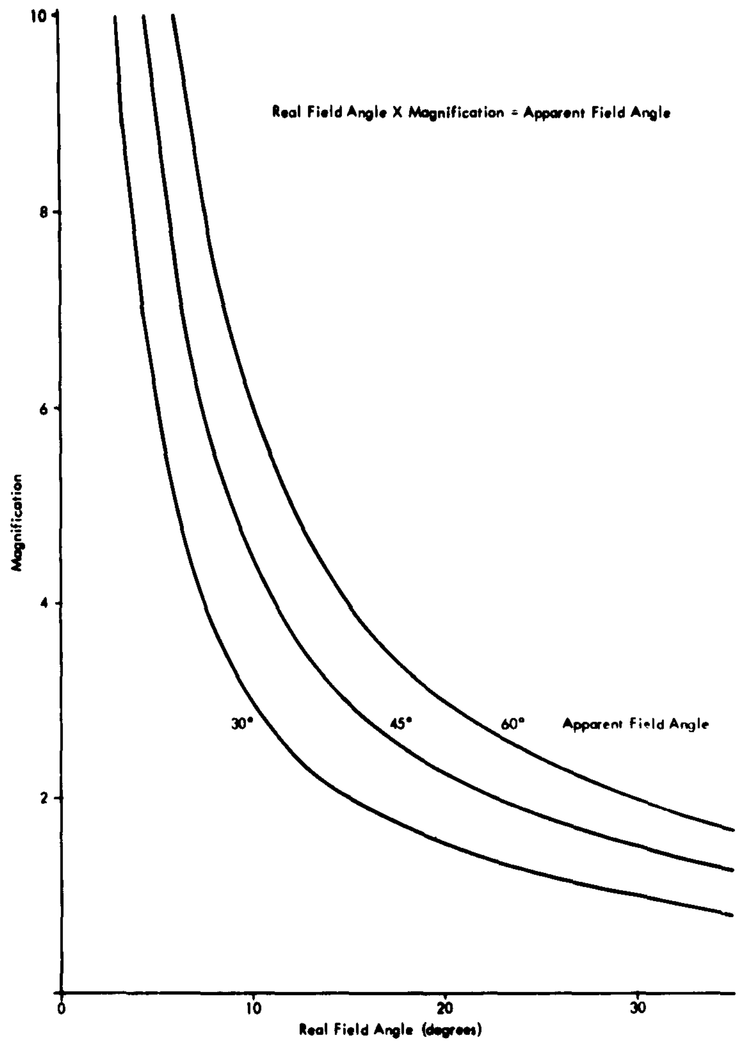

Figure 3-35. Magnification vs Real Field Angle vs Apparent Field Angle (Low Magnification)

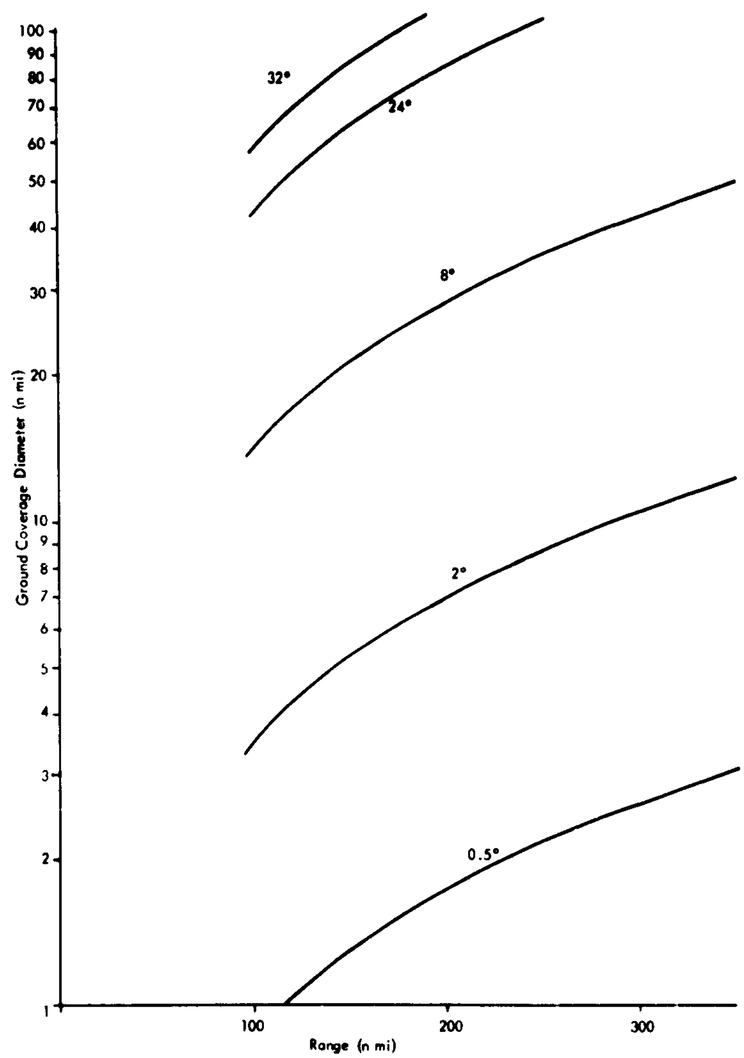

Figure 3-36. Ground Coverage vs Real Field Angle

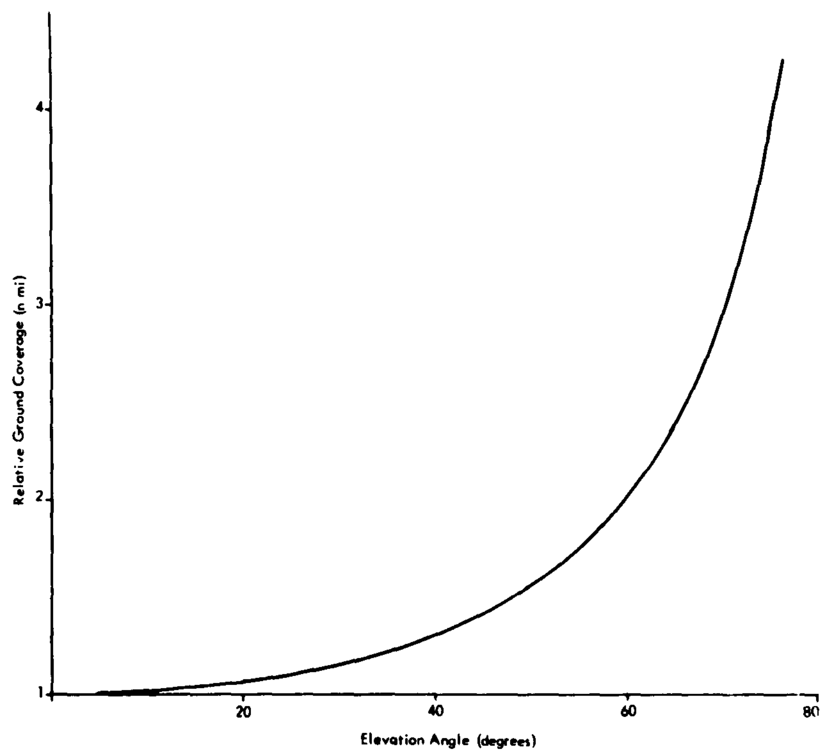

Figure 3-37. Increase in Ground Coverage
With Elevation Angle

specifications of objectives used in aerospace photography may be summarized briefly as those having:

- As long a focal length as possible
- As large an aperature as possible, consistent with this focal length

The combined parameters of long focal length, moderate to high speed, and high performance demand that near-zero aberrations be present over the entire usable field of view. This includes not only spherical aberration, coma, and astigmatism, but the chromatic variations of these aberrations as well. It is regard for these factors that has ultimately shaped the style and configuration of the photographic objective development.

A diffraction-limited system cannot be obtained unless an apochromatic solution is essentially obtained. The secondary spectrum, the remaining chromatic aberration after achromatization, is a most serious aberration in high-performance systems. This condition is aggravated when long focal lengths are desired.

If one considers the image characteristics of comparable reflective and refractive systems, by comparison the refractive approach appears inherently to yield the macimum information content. The central obstruction or annular aperture of the actaptric or catadioptric system, aside from the undesirable silhouetted exit pupil, has by comparison to the all-refractive system:

- A significantly larger diffraction pattern at any given f/number
- Reduced contrast rendition capabilities
- A relatively large veiling glare problem

The failure of a catadioptric system to render an Airy disc whose irradiance is equivalent to that of the refractive system limits its utility where the subject contrast is low and variable.

The number of possible lens froms capable of diffraction-limited imagery in long focal length and moderately high relative aperture is limited. Of particular interest are the objectives of the modified Gauss and Petzval types. With today's computers, large variety of glass types, excellent glass homogeniety, production of glass refractive index and dispersion within narrow tolerances, and ultra-high precision manufacture and assembly, it is not difficult to obtain lenses of the focal length, aperture and performance considered for this application.

3.2.2.3.4 Scanning - The scanning requirements for the IVSS are similar to those of a typical bombing periscope: servo driven gimballed optics with encoder readout. Because the scanning requirements for the target tracking mode have by far the greater impact on the system, the scanning optics study covered only this phase. Preliminary calculations indicated that the required aperture would be at least 7 inches in diameter. Having settled upon this line as a basis for analysis, various two-axis scanning systems which could be used with this aperture were considered. The ideal scanner would be described as light, compact and simple, having low inertia and convenient pointing controls. It would cause no image degradation, contrast loss, or light loss. Five two-axis scanning systems are listed and described below:

- Single mirror in two-axis mount
- Two 45-degree mirrors in full rotation mounts
- Two 45-degree prisms in full rotation mounts
- Double-dove prism in two-axis mount
- Two double-dove prisms.

3.2.2.3.4.1 Single Mirror - The single scanning mirror is capable of handling moderate field angles (up to about 15 degrees) for coverage 120 degrees by 180 or 360 degrees. The mirror is a flat eccentric elipse of which the high incident angles require a precise optical surface. A large eccentric elliptical flat with a precise optical surface presents a formidable task of optical fabrication. The mirror scans at twice its pitch rate and at a rate equal to its roll rate. Image rotation results from roll but not pitch. Most of the properties of this scanner indicate that it is relatively inconvenient for use with the IVSS acquisition and tracking system.

3.2.2.3.4.2 Two 45-Degree Mirrors - Two 45-degree mirrors can provide coverage of a full sphere except where the view is obstructed by the vehicle. The scan rate is equal to the pitch and roll rates. The mirrors are elliptical flats having relatively low eccentricity and moderate surface tolerances. They are not extremely difficult to fabricate. The two-mirror scanner has a significant weight advantage over all other scanners considered for the tracking system.

3.2.2.3.4.3 Two 45-Degree Prisms - Two 45-degree prisms have identical properties with the two mirror system with a few distinctions: for small field angles they weigh more but are slightly more compact; surface tolerances are less critical, particularly for large field angles; there are more optical surfaces on the prisms than on mirrors, large prisms are difficult to fabricate due to the problem of obtaining thick pieces of high quality optical glass.

3.2.2.3.4.4 Double-Dove Prisms – Double-dove prisms will cover more than a hemisphere. The image rotates for roll but not pitch. The prism consists of two identical 45-degree prisms, which scan at twice the pitch rate and equal to the roll rates. Prism angle tolerances are particularly critical as is the alignment tolerance between the two prisms. Angle and alignment errors lead to image doubling. The double-dove prism is impractical for the tracking system due to its great size and weight in this application and the difficulties which would be encountered in its manufacture.

3.2.2.3.4.5 Two Double-Dove Prisms – Two double-dove prisms could be used with the restriction that the coverage would be considerably less than 180 degrees in one direction. The advantage to the system would be that there would be two-axis scanning without any image derotation. This single advantage is far outweighed by the large size of the prisms and the resulting fabrication problems. The slightest misalignment would result in severe image degradation.

3.2.2.3.4.6 Conclusions – The most advantageous scanning configuration for the tracking system, all properties considered, appears to be two 45-degree mirrors. Although the comparison of scanning optics is made on the basis of a specific lens aperture, the implications are quite general for lenses operating at relatively small field angles. Specifically, the two 45-degree mirror system provides the lightest weight two-axis scanning system for a lens with any aperature size and focal length as long as the field angle is small.

The weight analysis is based on glass mirrors and prisms with a density of 0.1 pound per cubic inch. Mirror thickness is 1/8 of the mirror length. The weights in Figure 3-38 are based on optical elements slightly larger than the required optical size for fabrication considerations.

Another significant development in the scanning study was the advantages of an equatorial-type scanner over a conventional type altazimuth scanner. Like altazimuths, equatorials provide for motion of the optical axis about two mutually perpendicular axes; these are, however, no longer horizontal and vertical, but parallel to the vehicle's axis and at right angles to it (roll-pitch). The major advantage of the roll-pitch scan is that once the target is centered on the crossline the scan is entirely accomplished by the pitch servo except for minor corrections by the roll servo. It is a necessity for high acuity photographic recording.

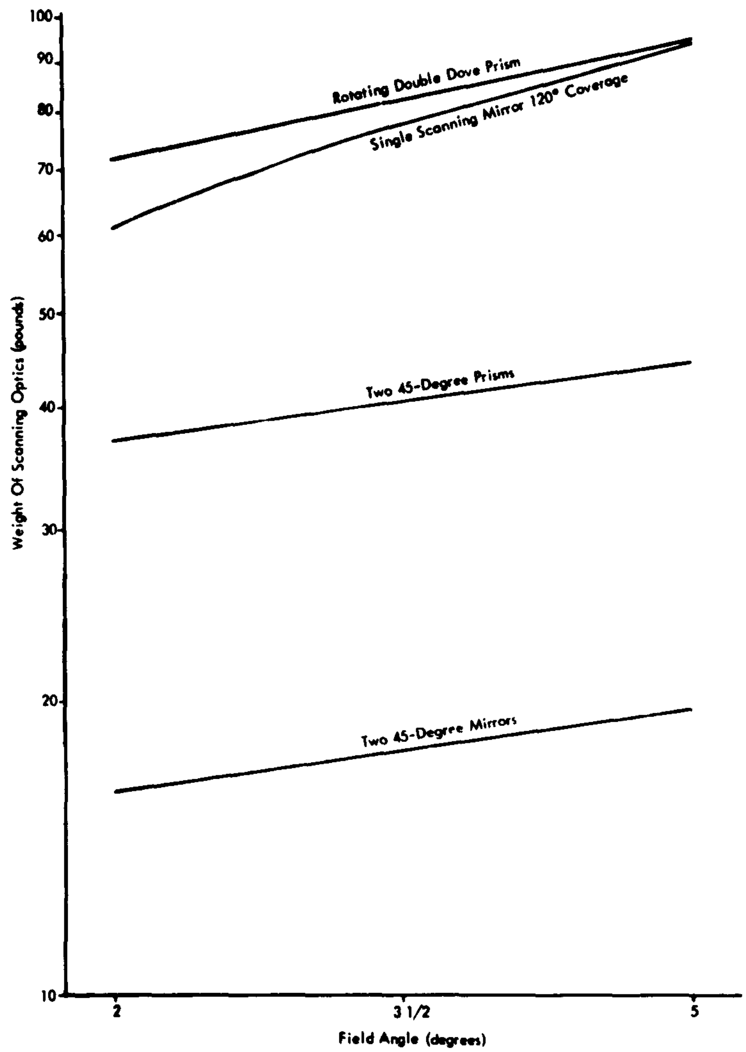

Figure 3-38. Weight of Scanning Optics (7" Aperture)

3.2.2.3.5 Focal Length - The focal length of the PTS objective lens must be long enough to obtain photographs compatible with experiment evaluation requirements. At the same time the relative aperture (f/number) should be kept numerically small to maintain a satisfactory level of image brightness for both the visual and photo tasks.

Considering factors, as image content capacity; excellence of available equipment, weight, and volume, the 70-mm format was selected. Figure 3-39 depicts the relationship of field angle and focal length for the 70-mm format. The relationships of photographic scale as a function of range and of focal length are shown in Figure 3-40.

3.2.2.3.6 Focus Adjustment - Focusing adjustments will be significant when tracking and observing space objects at close approach (less than 1 n mi). For a system of 36-inch focal length, the primary image plane will move about 1/5 inch as a target changes range from one mile to 500 feet. See Figure 3-41.

A perfectly corrected lens system will have a certain range, known as depth of focus, throughout which the image plane may be located without having an optical path difference exceeding the Rayleigh limit. This depth of focus may be applied in either direction from the true focus and is given by

$$\text{Depth of focus} = \pm \frac{\lambda}{\sin^2 U'_m}$$

To apply the Rayleigh limit, it is necessary to trace a ray from an axial object point, through the margin of the aperture stop, to its final intercept in the image on the axis. This ray will make an angle U'_m with the axis at the image. λ is the wavelength of the light used. For an f/4.5 optical system and a wavelength of 6000A, the depth focus is:

$$\text{D.F.} = \pm\, 0.0019 \text{ inch.}$$

The consistent and effortless presentation of well focused images is critically important to the observer throughout these ranges. The image motion must therefore be countered by automatically moving elements of the image forming, viewing and recording systems. Because of the variety of targets, ranges and configurations, open-loop focus systems are preferred, making small movements from infinity positions, rather than closed-loop systems. These movements are of the order of 1/5 inch $\pm$ 0.0005 inch (assuming about 150 lines per millimeter and optics about f/4.5).

The ideal method of refocussing is to make the camera itself moveable and also the unit of the visual system containing the field flattener, reticle

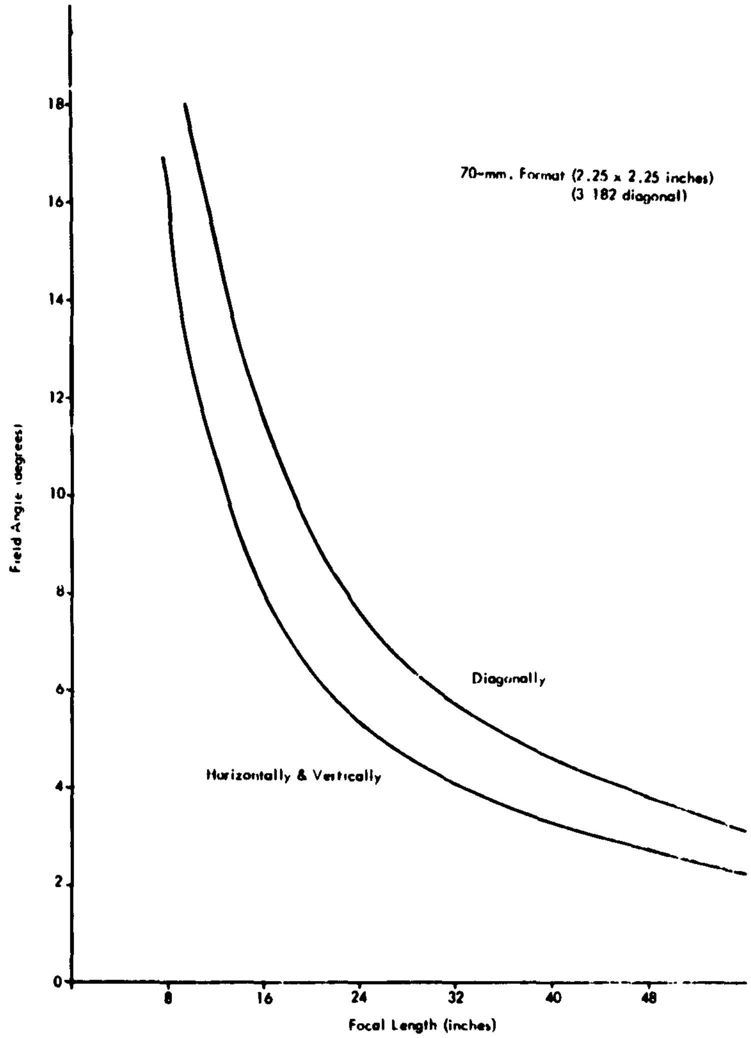

Figure 3-39. Field Angle vs Focal Length

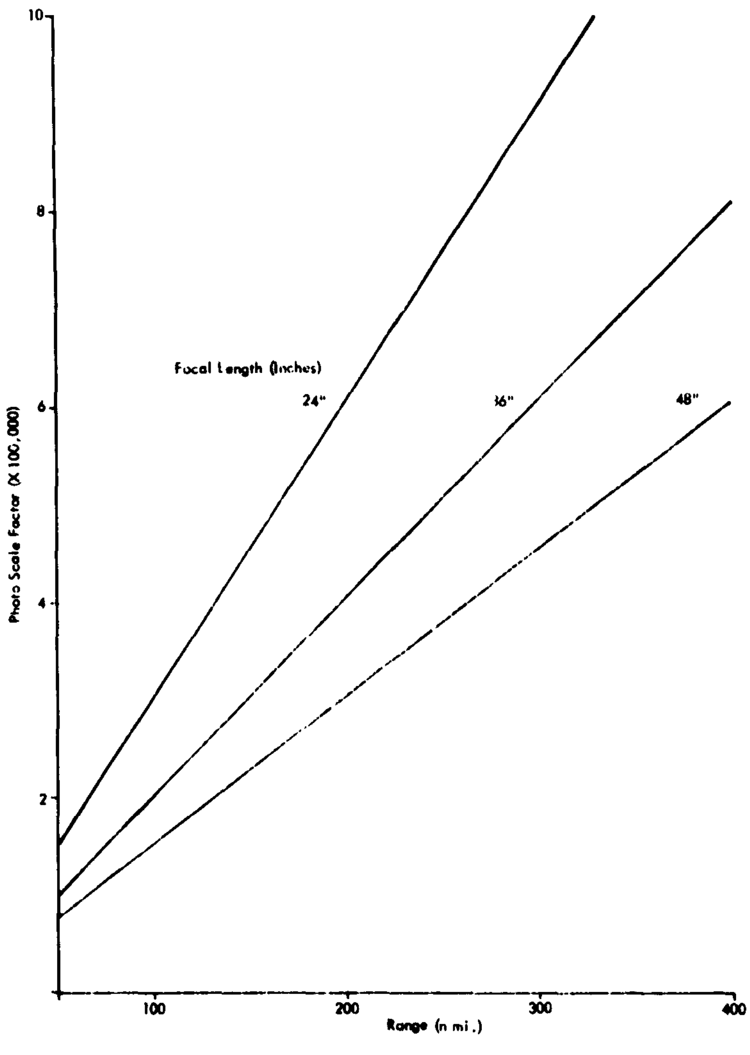

Figure 3-40. Scale vs Range vs Focal Length

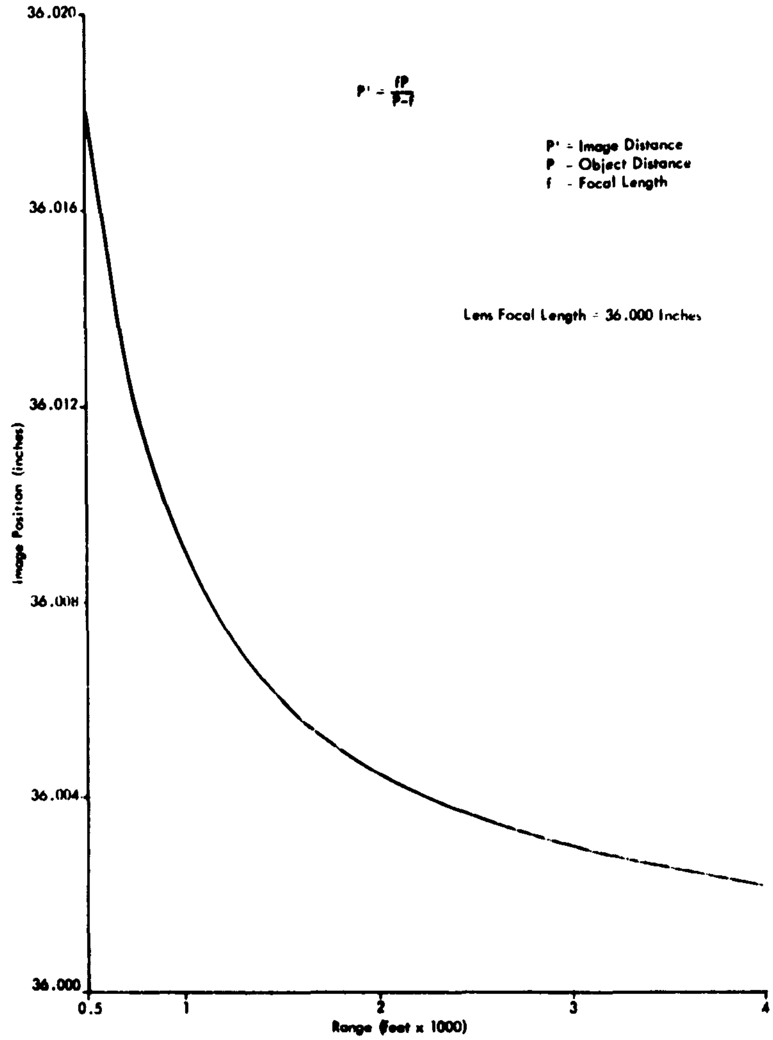

Figure 3-41. Image Shift vs Object Distance

(focal plane) and first relay lens. Between tracking tasks, the observers will be able to monitor both photographic and visual focus. Facilities will be provided for manual adjustments. Attention will be paid to the mechanical stability and rigidity of the basic PTS structure, so that it can always be easily placed in or restored to optimum infinity focus.

These adjustments are necessary, but not sufficient to ensure good records and accurate angular data. The need to isolate the experimental data from contamination caused by unexpected vehicle motion calls for a study of the structural rigidity of the vehicle frame to which angular tracking data is referred. During Phase I, study will be extended to cover the constraints imposed on system accuracy during boost and by manpower loading of the MOL vehicle. In addition to the evident mechanical sources of error, thermal effects will be studied. The steep thermal gradients between MOL cabin and the external optics, and the flow of background radiation through the optical system, both pose real problems in instrument design.

3.2.2.3.7 Image Derotation – An analysis of the mission requirements, experiment definition, and system configuration and dynamics indicate the image will rotate as the target is scanned at an angular rate which will be objectionable to the observer. The image rotational rate for an altitude of 160 n mi. tracking an object on the ground is plotted in Figure 3-42. This need for the visual image to be derotated should be substantiated by simulation. During a typical photographic exposure of 0.010 second or less a point 1 inch from the center of the photograph will rotate 5 microns or less. The photographic image quality will not be seriously affected by this small motion. However, this rotation of the image will need to be taken into consideration in the image measurements if the object is not close to the photo center.

All visual scanning periscopes for military uses have derotation systems. The state-of-the-art for derotation systems has been brought to high perfection by the development of the Air Force Y-series of bombing periscopes.

The derotation servo would be ac and driven by syncros. A differential on the pitch and roll scanning servos feed a control transformer on the input of the derotation servo amplifier.

3.2.2.3.8 Eyepiece – The main features that are required of an eyepiece are: imperceptible aberrations with the appropriate objective; a wide field; a flat field; a dark field, i.e., freedom from internal reflections which either produce ghosts or lessen contrast, or both; bright images,

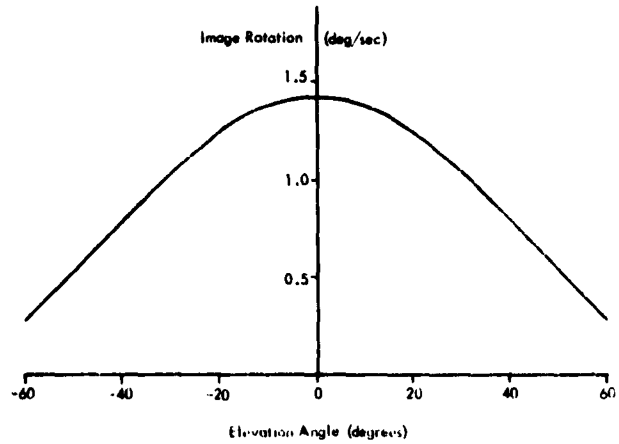

Figure 3-42. Image Rotation vs Scan Angle

i.e., the reduction to a minimum of light lost by internal reflection and by absorption; and sufficient clearance between the eye lens and the exit pupil to ensure comfortable observing. Eyepiece design has been brought to a high degree of perfection so that an eyepiece which meets the requirements of magnification, field angle, and exit pupil distance is not difficult to achieve. The size of an eyepiece is very much dependent on the joint requirements of field and eye clearance according to the relation:

$$\text{Diameter} = 2 \times (\text{eye distance}) \times \tan\left(\frac{\theta}{2}\right),$$

where θ is the apparent field angle. Figure 3.2.2-11 shows a graph of the relationship between size, clear eye distance, and apparent field angle.

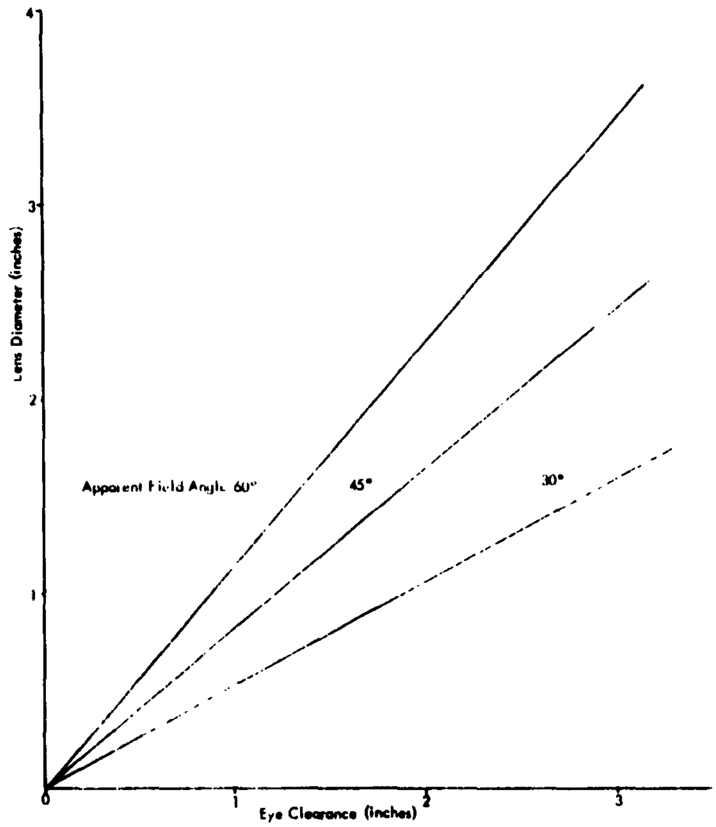

Figure 3-43. Lens Diameter vs Eye Clearance vs Apparent Field

A preliminary analysis indicates that zoom optics offer little advantage in acquisition tasks, where a large field is preferred, and that they should be unnecessary in tracking an acquired target. However, examination of extended areas such as cities, fleets or a large nearby satellite could well be expedited by a free choice of zoom magnification after acquisition. Built-in zoom systems offer rapid, continuous, and convenient power changes. Zoom systems give continuous power change, without the "blackouts" between power changes that occur in multiple lens systems, and the operator may adjust the power to the desired value for best seeing during the prevailing conditions of target contrast, atmospheric haze, and illumination.

3.2.2.3.9 Exit Pupil - The exit pupil size is governed by the objective diameter and the magnification. Its longitudinal location is determined by ocular type and focal length. Attention must be given to exit pupil size and eye clearance so that they conform to good human factor practices. A recommended eye relief is 1 inch. The change in exit pupil size with magnification for an 8-inch objective is shown in Figure 3-44.

3.2.2.3.10 Reticles - This section reviews the criteria that should be satisfied in the design of the acquisition and tracking reticle for the IVSS telescope, and proposes a design meeting them.

3.2.2.3.10.1 Width of Crosshair - The data presented by Holstein* suggests that there is a strong relationship between crosshair width, target size, and tracking ability. This study was done at the near point of visual fixation and used crosshairs that were well above threshold, from about 4 arc minutes to 2 degrees.

The targets considered ranged from 7 arc minutes to 4 degrees in width. Except for the smallest targets, a crosshair of about 7 arc minutes in width appeared superior. The smallest targets required a crosshair of about one half the width of the target. The inference here is that the main body of the crosshair segment should be about 6 or 7 arc minutes wide and begin to narrow within 15 arc minutes of the center. See Figure 3-44. The recommendations developed for rangefinder reticle** suggested a narrower line width, about 3 arc minutes with an open center.

* IBM No. 58-535-3

** C.H. Graham and L. A. Riggs - Summary of Research on the design of illuminated reticles, O.E. MSR-1059. Brown University. June 16, 1945.

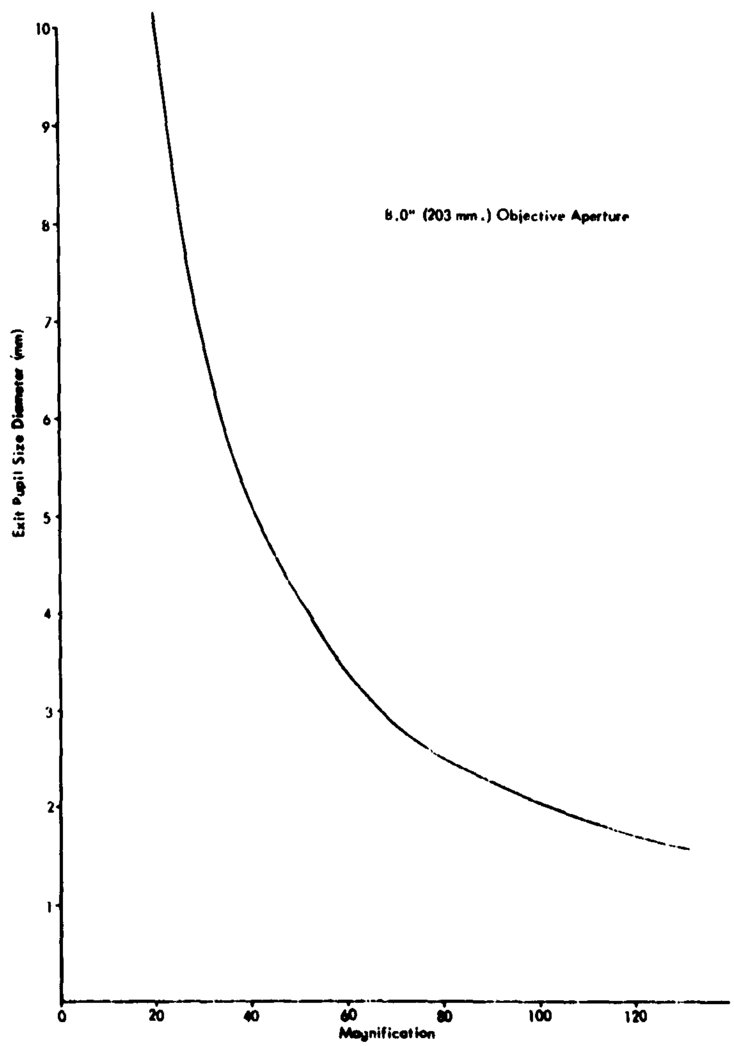

Figure 3-44. Exit Pupil vs Magnification

3.2.2.3.10.2 Extent of the Crosshair - The acquisition task will vary from the tracking task with respect to reticle design in that general location is more important than precise location of the crosshairs. The observer would want to know when the crosshairs are in the general target area. Once he is assured of this, he may switch to the tracking mode.

During the acquisition phase, the general configuration of the field of view may be very important with respect to the gross contours of the terrain. During the tracking phase, the gross characteristics are relatively unimportant, here the observer wishes to maintain a relationship between one fine feature of the field of view and the intersection of the crosshairs.

3.2.2.3.10.3 Illumination - The reticle system may be either opaque or illuminated. Investigation indicates that an illuminated reticle would be better for use in this system, particularly if the reticle illumination will be confined to wave lengths not common in the environment, such as a deep red. The operator should be able to control the intensity and wavelength composition of the illuminated form.

3.2.2.3.10.4 Supplementary Information - Three types of supplementary information may be considered in addition to the previously mentioned orientation information. These are: (1) the field of view to be covered in the next magnification, (2) comparison marks to determine ground distances, and (3) a fixation point for scotopic viewing.

Small distinctive marks could be used to determine the field of view for the next magnification. These would be particularly important if the magnification steps were not equal.

Depending upon an analysis of the mission, the intelligence task could probably be removed, for the most part, from real time telescope viewing to the examination of static displays. Some capability for the determination of size should be included in some of the reticles. This capability should be at least sensitive to the point of determining ship class.

The acquisitional and tracking reticle design recommendations are as follows:

- Crosshair width - 6 minutes of arc.
- Center configuration as shown in Figure 3-45 (a) and overall configuration as in Figure 3-45 (b).

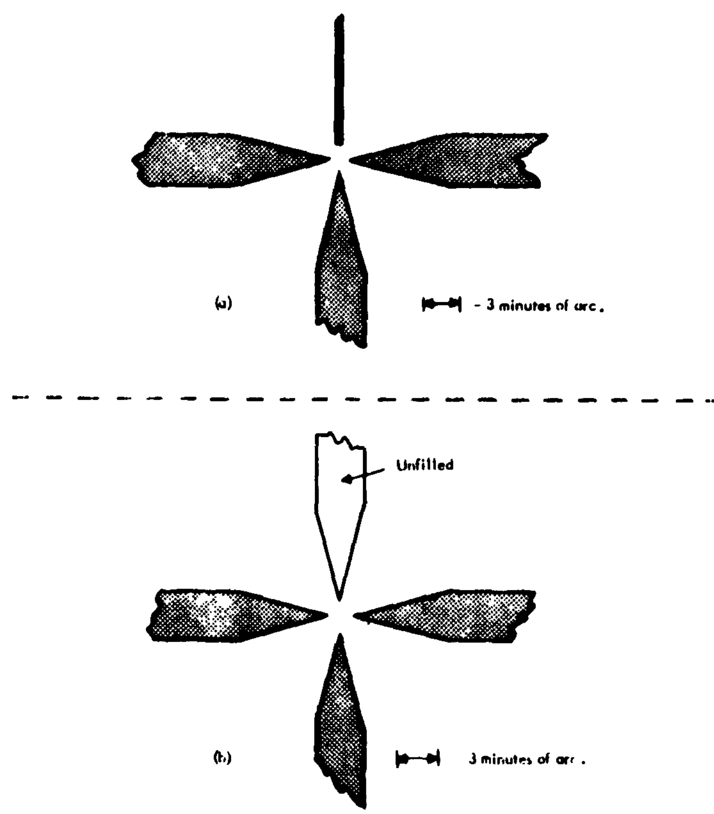

Figure 3-45. Reticle Crosshair Width

- Be capable of opaque and selectivity illuminated use.
- Intelligence data to be added to reticles for magnifications of 15 to 20X and higher.
- Reticle length - 5 degrees.
- Contain next field of view information.

3.2.2.3.10.5 Driftmeter Grid Reticle – A grid reticle (shown in Figure 3-46) would be desirable for aligning the vehicle to the orbit plane and/or ground velocity vector.

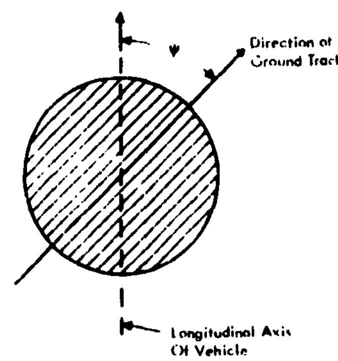

Figure 3-46. Driftmeter Reticle

What is envisioned here is that the astronaut would slave the PTS to look straight down at the Earth. The astronaut would then align the grid lines with the movement of the Earth as is done normally in aircraft drift scopes. This reticle would require pickoffs to measure the angular deviation of the grid lines with respect to the longitudinal axis of the vehicle (ψ). The electrical interface of this particular reticle would be both automatic, as taken from the PTS gimbal angles for reticle rotation of the image, and by the manual override from the display console to align the grid lines to the velocity vector.

3.2.3 PTS Coupled Camera

3.2.3.1 General

In specifying the tasks to be performed by astronauts on the MOL, some importance has been attached to the assessment of a trained observer's ability to acquire and track targets of interest. In particular, this assessment should be compatible with a determination of angular velocity to an accuracy of 0.2 percent. This accuracy in the angular velocity of the line-of-sight, (LOS), will be referenced to inertial space. The IVSS will include the optical tracking systems, but it must also record the progress of a tracking maneuver and measure the accuracy of the observer. A photographic sampling system will provide a permanent record for analysis on the ground and, with on-board processing, will allow the astronaut to evaluate his performance and apply corrective procedures on subsequent trials.

Following the discussion on cameras and film, the applicability of low-light-level TV to complement the camera for low illumination and contrast is discussed.

3.2.3.2 Camera - PTS Tie-in

The light received through the scanning optics and objective lens will be shared between the visual and photographic systems. First considerations showed that a time sharing is possible because of the finite "flicker frequency" of the eye, and the low duty cycle of most cameras. Investigated were time-sharing mirror systems that operate at a chopping frequency sufficiently high that image jitter at the highest expected resolutions and angular velocities do not hinder the observer. Such a mirror would be rotary rather than "flipping", in order to minimize mechanical transients in the optical system, and would be phase-locked to the recording camera shutter. The analyses of the experiment definition, however, showed that a high resolution photographic system was necessary, and a rotating mirror would most probably degrade the photographic quality. Therefore, it was decided that an 80 percent reflecting, 8 percent transmitting, metallic beamsplitter would be better. This method provides the photographic image take-off behind the objective lens. The rays for the photographic image would be reflected from the first surface of the beamsplitter.

3.2.3.3 Format Size

Considering information content, weight, volume and equipment availability,the 70-mm film size with a 2.25-inch-square image (or 2.25-inch diameter circular field, if preferred, with data blocks in the corners) represents an excellent compromise.

The field and ground coverage obtained with the 70-mm format when used with different focal length lenses are shown in Figures 3-39 and 3-40.

3.2.3.4 Film

The characteristics of Kodak aerial films are given in Table 3-7. The analyses of the system requirements shows that the Kodak SO-243, Special High Definition Aerial Film, is preferred. A thinner base film, with similar characteristics but somewhat more difficult to handle because of its thinness, is Kodak 4404 Aerial Film. Where weight and volume are severe requirements, it is recommended that the 4404 film be used. Weight curves for these two films are given in Figure 3-47.

3.2.3.5 Cameras

3.2.3.5.1 General — The problem of recording the progress of a tracking system is subject to considerable trade-off activity; thus, provision should be made for a selection of cameras (not necessarily as an option of the operator). Consequently, the camera stations will be designed on the principle of a modular system, where any one of several cameras can be attached depending on the mission. In reviewing the choices of cameras, the intention is not to indicate that many cameras, or all of them, should be carried on a flight, but rather to provide a basis for selection.

For the purpose of the discussion, the camera is defined as the mechanism which supplies, exposes, indexes, and stores film used for recording the images formed by the optical system.

Cameras fall into several basic categroies; however, the two of interest in recording the images expected in the IVSS are the frame camera, and the cine camera. The frame camera includes cameras with exposure rates up to four or five per second. The cine camera group refers to systems with frame rates exceeding five per second.

The camera should be of an established, proven model so that the complication of proving a new camera is not added to the already considerable development task. An illustrative group of cameras currently available are shown in Table 3-8. The illustrative group of cameras does not include all currently available systems, some of which may have distinct weight or volume advantages. The detailed evaluation of all cameras potentially useful in the IVSS will be a part of the proposed Phase I.

The frame camera will generally be much smaller than the cine camera, will have a smaller film capacity, and may not have a separate magazine. Usually, the frame camera is available in 35- and 70-mm sizes. The

Table 3-7

CHARACTERISTICS OF KODAK AERIAL FILMS

Availability	KODAK Film	Film Type No.	Sensitivity	Description and Special Properties	Base Type	Nominal Base Thickness (mils)	Gel Backing	Aerial Exposure Index[1]	Resolving Power[2] (lines/mm) T.O.C. = 1,000:1	Resolving Power[2] (lines/mm) T.O.C. = 1.6:1	RMS Granularity[3]	Safelight Filter (WRATTEN Series No.)	KODAK Developers[4]	KODAK VERSAMAT Developer Type
FACTORY STOCKED (in certain sizes)	DOUBLE-X AEROGRAPHIC (ESTAR Base)	1405	[redacted]	Standard film for mapping and charting, high dimensional stability	ESTAR	4	Clear	125	85	38	0.100	Total Darkness	DK-50	A
	PLUS-X AEROGRAPHIC	5401		High definition mapping film on topographic support	acetate butyrate	5.2	None	80	115	40	[illegible]	Total Darkness	D-19, D 76	A
	SUPER-XX AEROGRAPHIC††	5425		Standard film for aerial mapping and charting	acetate butyrate	5.2	None	100	75	30	0.105	Total Darkness	D-19, DK-50	A
	PLUS-X AERECON	8401		Medium speed, high altitude aerial reconnaissance film	triacetate	5.2	None	80	112	40	0.065	Total Darkness	D-19, D 76	A
	TRI-X AERECON	8403		High speed aerial reconnaissance film	triacetate	5.2	None	200	71	22	0.140	Total Darkness	D-19, D 76	A
	Infrared AEROGRAPHIC	5424	IR	For reduction of haze effects, water location, and forest surveys	acetate butyrate	5.2	None	125[5]	80	28	0.115	Total Darkness	D-19	A
	EKTACHROME Infrared AERO	8443	IR	False color reversal film for camouflage detection, forest surveys	triacetate	5.2	None	10[6]	–	–	–	Total Darkness	KODAK Process E-2/E-3	–
	EKTACHROME AERO	8442	COLOR	Color reversal film for medium to high altitude reconnaissance	triacetate	5.2	None	25[7]	–	–	–	Total Darkness	KODAK Process E-2/E-3	–
SPECIAL ORDER†	Special EKTACOLOR Aerial	SO 276	COLOR	Color negative film for aerial photography at low altitudes	triacetate	5.2	None	10[7]	–	–	–	Total Darkness	KODAK Process C-22	–
	Special EKTACHROME Aerial	SO 282	COLOR	Color reversal film for low-altitude reconnaissance	triacetate	5.2	None	6.0	–	–	–	Total Darkness	KODAK Process E-2	–
	AEROGRAPHIC Duplicating	5427	BLUE	For duplicating AEROGRAPHIC base negatives on low-shrink support	acetate butyrate	5.2	None	*	141	55	0.043	1A (Light Red)	DK-50, D 76	B
	Aerial Recon Duplicating	8427	BLUE	For duplicating reconnaissance base aerial negatives	triacetate	5.2	None	*	141	56	0.043	1A (Light Red)	DK-50, D-76	B
	Fine Grain Aerial Duplicating	8430	BLUE	For duplicating high-definition aerial negatives	triacetate	5.6	None	**	285	120	[illegible]	1A (Light Red)	DK-50, D-76	B
	Special Aerial Duplicating (ESTAR Base)	SO-115	BLUE	For duplicating aerial negatives, high dimensional stability	ESTAR	4	Clear	*	135	63	0.045	1A (Light Red)	DK-50, D 76	B
	Special Aerial Duplicating (ESTAR Thick Base)	SO 117	BLUE	For duplicating aerial negatives, maximum dimensional stability	ESTAR	7	Clear	*	135	63	0.045	1A (Light Red)	DK-50, D 76	B
	PANATOMIC-X Aerial (ESTAR Thin Base)	4400	[redacted]	Intermediate speed, thin-base, high-altitude reconnaissance film	ESTAR	2.5	Dyed	20	170	85	[illegible]	Total Darkness	D-19, D 76	A
	PLUS-X Aerial (ESTAR Thin Base)	4401		Medium speed, thin-base, high-altitude reconnaissance film	ESTAR	2.5	Dyed	64	165	48	[illegible]	Total Darkness	D-19, D 76	A
	High Definition Aerial (ESTAR Thin Base)	4404		Thin base, highest definition for high-altitude reconnaissance	ESTAR	2.5	Dyed	1.6	475	280	0.023	Total Darkness	D-19, D 76	Note 9
	Special PLUS-X Aerial (ESTAR Base)	SO 135		Medium-speed, high dimensional stability for mapping	ESTAR	4	Clear	80	112	43	[illegible]	Total Darkness	D-19, BIMAT Process[10]	–
	Special PANATOMIC-X Aerial (ESTAR Base)	SO 136		Intermediate speed, high dimensional stability for mapping	ESTAR	4	Dyed	20	165	85	[illegible]	Total Darkness	D-19, BIMAT Process[10]	–
	Special Fine Grain Aerial (ESTAR Base)	SO 226		Moderate speed, fine grain, for high altitude mapping	ESTAR	4	Dyed	6.0	335	112	[illegible]	Total Darkness	D-19	Note 9
	Special High Definition Aerial (Gray Base)	SO 243		Slow speed, high definition, for high-altitude reconnaissance	triacetate	5.25	None	1.6	485	285	[illegible]	Total Darkness	D-19	–

†For special-order films, the data represents averages for relatively few coatings. Future coatings may show variations as products are improved to meet changing customer requirements.

††Has extended red sensitivity.

*About two times the speed of KODABROMIDE Paper No. 2 or KODAK RESISTO Rapid Paper No. 2

**About 1/8 the speed of KODAK AEROGRAPHIC Duplicating Film, Type 5427

1. These indexes are for use with the KODAK Aerial Exposure Computer to determine the correct camera exposure for aerial (air-to-ground) photography.
2. Data given for [illegible]-minute development at 68 F in developer shown in dark-face type.
3. Root-mean-square (rms) granularity; values represent the standard deviation in density produced by the granular structure of the material when a uniformly exposed and developed sample is scanned by a densitometer having a small measuring aperture. The data given here are for a net density of 1.0 (excluding the density of the support) and for a circular scanning aperture whose diameter is [illegible]. The numbers indicate the magnitude of the impression of graininess which would be produced if the samples were examined visually.
4. The developers shown in dark-face type were used to determine the speed and image-structure data shown. Slight differences in these characteristics may result when other developers are used, such as those developers shown in light-face type.
5. Without a filter
6. With KODAK WRATTEN Filter No. 12
7. A haze filter such as the KODAK HF-3, HF-4, or HF-5 Gelatin Film Filter is suggested.
8. A KODAK WRATTEN Filter No. [illegible] may be used if desired.
9. Can be processed in a KODAK VERSAMAT Processor with special chemistry.
10. Use KODAK BIMAT [illegible], [illegible], with KODAK BIMAT Film (ESTAR Base), Type SO-111 for web processing.

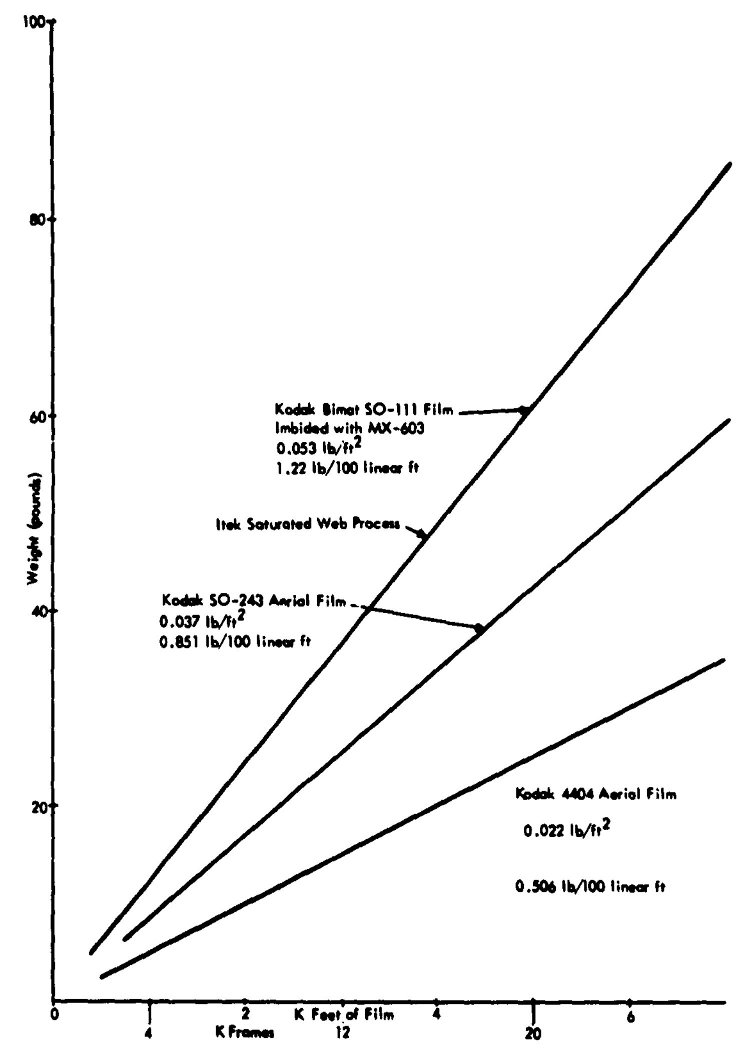

Figure 3-47. Negative and Processing Film Weights (70-mm Width)

Table 3-8

FILM AND CAMERA TRADE-OFF DATA

Type	Film Size (mm)	Camera	Frame Rate (per sec)	Film Capacity (feet)	Weight (lb.)	Vol-ume. (cubic feet)	Power Req. (watts)
Frame	35	Robot Royal	5	30 & 100	4	1/8	80
Frame	35	Beattie Varia-tion	4	100 & 200	20	1/4	175
Cine-pin	35	Flight Re-search IVc	5-40	100/200/400/1000	11	1/8	100
Frame	70	Itek KA61	4	50/100	6	1/8	150
Frame	70	Maurer P2	6	10/50	5	1/8	90
Frame	70	Maurer P-220	6	15/30/100	6-8	1/8	110
Sequence	70	Hulcher 70	5-50	100/400/1000	80	3/4	475
Cine-pin	70	Photosonics 10A	5-80	100/400/1000	120	1.2	700
Cine-pin	70	Flight Re-search V	5-80	100/400/1000	80	1.2	700

shutter mechanisms generally limit the performance of frame cameras; thus, the rotating disk shutter characteristics of cine cameras may prove more desirable.

The cine cameras fall into three categories: (1) the pin register, held-film type; (2) the moving film, rotating prism type; and (3) the "sequence" type, where frame-to-frame register is not held.

3.2.3.5.2 Small, 35-mm Frame Cameras — The factors which enter into an analysis of cameras can be illustrated by comparing the units listed in Table 3-8. First, the small, lightweight 35-mm frame cameras are restricted to a limited film capacity, and few models have the automatic film mechanisms required. Also, the use of a magazine, which is preferred for IVSS, is a feature not generally found in 35-mm cameras.

A further restriction in small frame cameras is the shutter mechanism. The typical 35-mm frame camera has a between-the-lens shutter of the multiple blade type, where the shutter is integral with the lens. In the IVSS, a separate shutter would be required near the focal plane, and most 35-mm cameras will not adapt to this mode of operation. Thus the lightweight, simple camera, while attractive as a recording camera, is

severely limited for this particular application, even though there would be no major reduction in optical resolution due to internal vibration or film movements.

To accommodate film loads of 50, 100, or 200 feet, the frame camera requires several modifications. Particular among them is the need for film drives which compensate for the increased inertia of the film on the supply and take-up spools. This problem is solved in the cine camera by providing spool drives as well as a film drive, so that start and stop characteristics do not degrade the camera performance. Thus, the cine camera achieves high frame rates, but is considerably heavier than the 35-mm camera due to the film transport system.

3.2.3.5.3 The 35-mm Cine Camera — The cine camera can be used at rates as low as 5 fps, but allowing for drive rates of 20, 30, or 40 fps increases the weight. The 35-mm cine camera is a common system; however, most of these have heavy structures to keep camera-generated vibrations to a minimum for the maintenance of good resolution. Further, the versatility required of the recording camera (variable speeds, and film loads) increases the weight, as does the autonomous magazine.

The IVSS camera requires a low inertia, fast cycle shutter. The familiar multi-blade type cannot cycle at high rates, and is susceptible to high failure rates at even 4 to 5 frames/second. Commonly, the cine or sequence camera utilizes a rotating disk shutter with a variable segment for exposure control. The shutter motor and synchronization requirements add weight and control complexity.

The requirements of the cine camera outlined above account for the rather drastic increase in size and weight when the frame rate rises above 4 or 5 per second.

The multiplicity of moving mechanisms in 35-mm cine cameras vibrates the film plane. The heavy weight of the system helps reduce this effect, but generally a maximum film plane resolution of only 100 lines/mm is possible with presently available commercial cameras.

3.2.3.5.4 The 70-mm Frame Cameras — The selection of 70-mm frame cameras is considerably smaller than that of 35-mm cameras, but aerial photography has been responsible for most of the camera designs available. Thus, such features as magazines, and shutters automatic film drives, are generally available.

Some cameras have built in IMC (image motion compensation) film drives. These drives advance the film during exposure to prevent the image motion imparted by the moving camera from blurring the image. The inclusion

of these drives, however, is not required for the PTS coupled camera. Some of the cameras, such as the KA61, also prove an in-camera processing capability which may be valuable.

The features of 70-mm frame cameras are virtually the same as those of the 35-mm cameras, with a resolution of 150 lines/mm attainable with a specially stabilized camera.

3.2.3.5.5 Sequence Camera — The sequence camera, which does not register frame to frame, is somewhat simpler than the pin register cine camera and consequently is smaller and lighter. However, because the sequence camera drive "jerks" the film, vibration is a big problem, limiting resolution to about 60 to 70 lines/mm. The cine camera, with register, is capable of a 90 to 100 lines/mm resolution, due to its increased precision and weight.

3.2.3.5.6 Summary — In selecting cameras for the IVSS, the factors of format, size, frame rate, weight, film capacity, and resolution must be weighed with the total system requirements. Such additional features as multiple exposure, which is easy with a slotted disk shutter, but difficult with a blade shutter, may swing the balance of selection. IBM will consider all of these features when making a selection.

3.2.3.6 Data Block

During data reduction complete detailed information regarding roll and pitch angel and time must be available. The accuracy of these indications will be the limiting factor in determining the actual rates and errors of the IVSS.

During data reduction, complete detailed information in a data block will be presented in the corner of each frame of each camera in an unused format area. This will be accomplished by presenting at a common station the following information:

- Exposure time
- Exposure select
- Frame number
- Film type
- Frame rate
- PTS gimbal angles
- Vehicle attitude
- Vehicle rates
- GMT
- Target latitude
- Target longitude

Before being optically relayed and inserted on the film, this data block format will be reduced. This data will be frozen at the beginning of the exposure; changes will be recorded on the next frame.

One current method of presenting the digital information simply is on the face of a small CRT tube. For this, blips around a circular scan indicate a bit in each determined segment of the circle. This system has sufficient light intensity to be used in the optical relay system, and leaves an easily readable record on film. The precision CRT read-out is duplicated using a coarse, arabic system so that quick analysis can be made without conversion from digital problem. This technique is one of the candidate systems being considered to permit the above-listed data to be recorded on film.

3.2.3.7 Film Processing

After careful consideration of the several processing modes available, IBM concluded that the Kodak Bimat process and the ITEK saturated web process offer the best techniques when considering such trade-off parameters as weight, space, image uniformity, reliability, operator safety, and freedom from catastrophic failure. The resolutions produced in these processes are directly comparable with good field processing and closely approach controlled laboratory processing. Among the systems considered and discarded are liquid bearing, viscous layer, liquid bath, and tank.

Among the important advantages of the Bimat and web processes in space applications are:

- The soaked web offers no solution-containment problem.
- A positive image is produced for immediate use (Bimat process)
- A high-quality negative is produced.
- The materials are simple and convenient to handle.
- Separate fixing is not required.
- Automatic, unattended processing is possible.
- Fresh processing solution is used on all film areas, ensuring consistent and reproducible results.
- No crystalline deposit is left on the films after separation.
- Processing is not affected by position or orientation of the equipment.
- The positive and the negative can be washed to provide archival permanence.

The Kodak Bimat process is a form of the diffusion transfer process, employing Kodak Bimat processing film (estar base) Type SO-111 moistened with processing solution (imbibed with MX-603 for processing SO-243 aerial film). The Bimat film contacts the negative to be processed for a prescribed period of time, after which the two films are separated. The usual negative image is developed in the film, while in the preferred form of the process, a positive image is simultaneously produced in the processing film.

To insure maintaining its physical and chemical properties for 30 days, the Bimat films should be stored at 40°F. The processing time with Bimat and SO-243 is from 5 minutes to 30 seconds for a temperature range of 60°F to 90°F.

The ITEK saturated web process consists of a web material, a low-density polyethylene of approximately 80 percent void volume and saturated with a monobath solution, and a combination of developer and fixer. The development time is from 5 to 2 minutes for a temperature range of 70°F to 90°F. In sealed containers the ITEK film can be stored more than 12 months at 70°F.

The weight curve for these materials is given in Figure 3-47.

3.2.4 Low Light Level Television System

3.2.4.1 Introduction

The use of a low-light-level television camera in the IVSS system can enhance sighting. With the aid of light amplification it is possible to record phenomena that the human eye cannot observe or, even at its best, cannot sense. In addition, the light amplifier can be used to photograph objects at light levels for which present photographic systems are not sufficiently sensitive. There exist also, many situations in which the intensification of the light is not as essential as the necessity to increase the contrast between the objects in the field of view as they are presented in the intensified image to the human eye or recording device. Thus a light amplifier, in addition to being able to detect the lowest light levels that are of interest, can also permit an arbitrary increase in contrast. At the present state-of-the-art, a system capable of fulfilling the intensification and contrast enhancement requirement is the low-light-level closed-circuit-television system. It has been shown both theoretically and experimentally, that brightness levels too small to be sensed or easily overlooked by the unaided human eye may be readily perceived visually from the cathode ray tube screen of such a light amplifier.

The necessary change in contrast can be achieved with proper circuitry in the video amplifier of the closed-circuit-television system. The video amplifier circuitry can also be built in such a manner that arbitrary threshold and amplitude limiting of the signal permits any amount of the signal to be suppressed, and only that portion of the signal containing pertinent information is amplified. The remainder of this discussion is concerned primarily with the sensor since this is the key component in the system. Before discussing the sensor, it should be noted that this system has the inherent capability to aid in the daytime tracking of moving objects, such as space vehicles, by suppressing all non-moving objects (background)

such that only the object of interest is in the image plane. This method has been employed in astronomical observations and should be further investigated in the next phase of the study.

In addition, this system can be used for mapping when radar and radio silence is imposed.

3.2.4.2 Sensor

Investigation to date has revealed that a sensor suitable for the application is the supersensitive intensifier image orthicon. An image intensifier is an evacuated envelope containing a photo-emitter at some distance from a phosphor (see Figure 3-48). An image incident on the photo-emitter creates free photo-electrons which are accelerated through a high potential and focused on a phosphor, whereupon the original light image is recreated as a visible light image of greater brightness. This image is in turn coupled to the image orthicon and is eventually converted to an electrical signal.

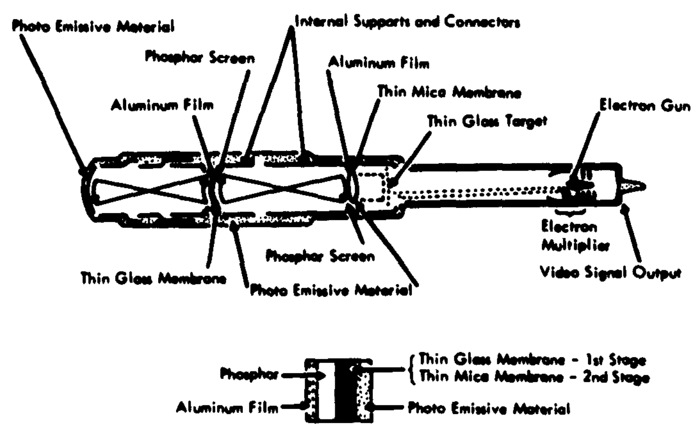

Figure 3-48. Image Intensifier Tube

Figure 3-49 compares the unaided human eye with the present state-of-the-art of a closed-circuit-television light amplifier using a fast optical system and a cooled double-stage intensifier image orthicon. By cooling the primary Photo-Cathode of the intensifier image orthicon pick-up tube, the fluctuations in the photo emission process become practically the only limitations in performance which have to be considered.

Factors which determine the superiority of light amplifier systems employing contrast enhancement are:

- Sufficient quantum efficiency and homogeniety of the photo cathode in the pick-up tube
- Proper cooling of the front end of the tube to avoid the practical limitation of the photo-cathode dark current
- Enough preamplification to overcome the scanning beam noise
- Adequate storage capability of the target plate
- Limitations due to scintillation.

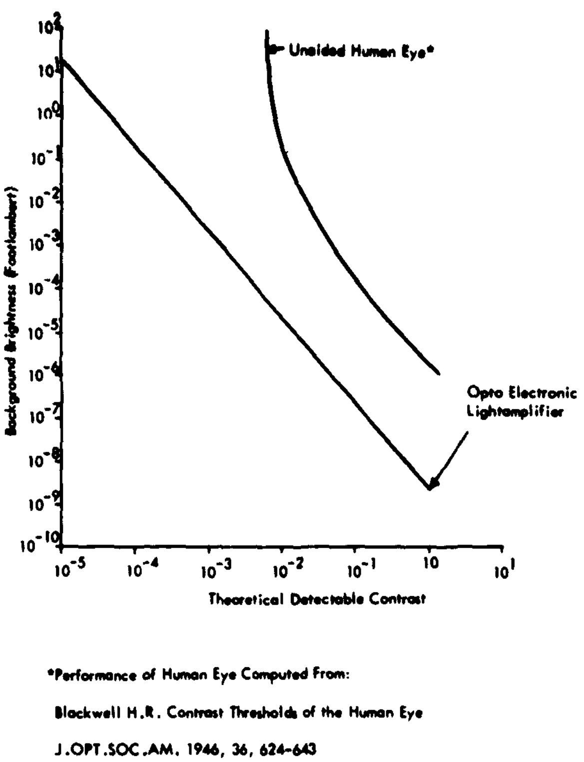

Figure 3-49. Background Brightness vs Theoretical Detectable Contrast

Although the image intensifier orthicon has a lower threshold than the image orthicon without the intensifier, it does have the disadvantage of lower resolution when the illumination of the cathode falls below about 10^{-4} foot candles. This is shown on Figure 3 - 50. The penalty for low-level detection is a reduction in resolution although the limit on illumination of the photo cathode is 10^{-8} foot candles. But, the fact remains that with either, overall performance is superior to that of the eye. A parametric study is required to determine which device is more applicable to IVSS. This requires analyzing the illumination at the image plane under various meteorological conditions.

Another advantage of the television system is that a shorter exposure time is needed than would be the case with conventional photography. The finer-grained photographs normally require longer exposure times for the same density than the coarser-grained plates do, but the finer-grained plates show more detail, and also smaller differences in local density variations can be detected. The gain in the image converter tube makes it possible to use reasonable exposure times with the finer-grained plates. (Important for tracking purposes).

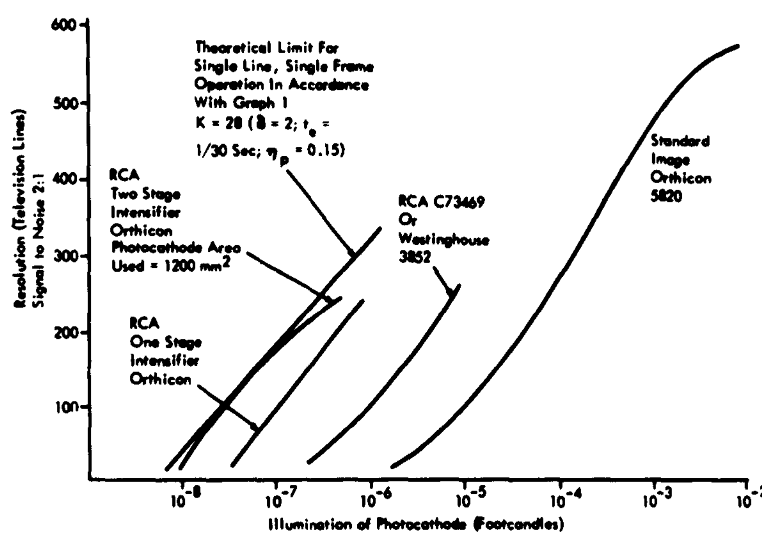

Figure 3-50. Pick-Up Tube Performance Compared to the Theoretical Limit Detectability

The best method of providing the required increase in contrast and suppression of background is a scanning system whereby the threshold can be determined arbitrarily by proper biasing of the video amplifier system employed. The desired increase in contrast can be obtained by direct suppression of a constant "background" from the whole scene by means of the electronic amplifier. The amount of background which can be suppressed is determined by the statistical fluctuations in the background. Figure 3-51 shows the type of operation performed on the electrical signal to achieve these results (static background).

The electronic modifications of the image which represent the signal obtained as the scanning beam moves across the target plate is accomplished as follows. The background noise is illustrated by the waviness. The upward slope from left to right is the result of a gradual shading in the sky within the field of view. (This can be corrected by shade controls and the results are shown.) The picture gamma control circuit is an electronic nonlinear device that permits one to increase the contrast.

The threshold limiter makes it possible to suppress the lower portion of the signal below a selected level, so that it constitutes that part of the circuitry which weakens or eliminates the background.

The amplitude limiter permits one to limit the upper portion of the signal thus removing the fluctuations in that portion of the signal caused by the viewed object.

3.2.4.3 Recommendations

It has been shown that a low-light-level television system can enhance the functions of IVSS in that it is superior to the unaided eye as a sensor because of its inherent ability to be used for tracking of space objects in daylight. In fact, the use of optical filtering to improve the contrast should be investigated.

To this end, a more refined systematic analysis is recommended which will result in a set of parameters upon which an engineering design can be realized.

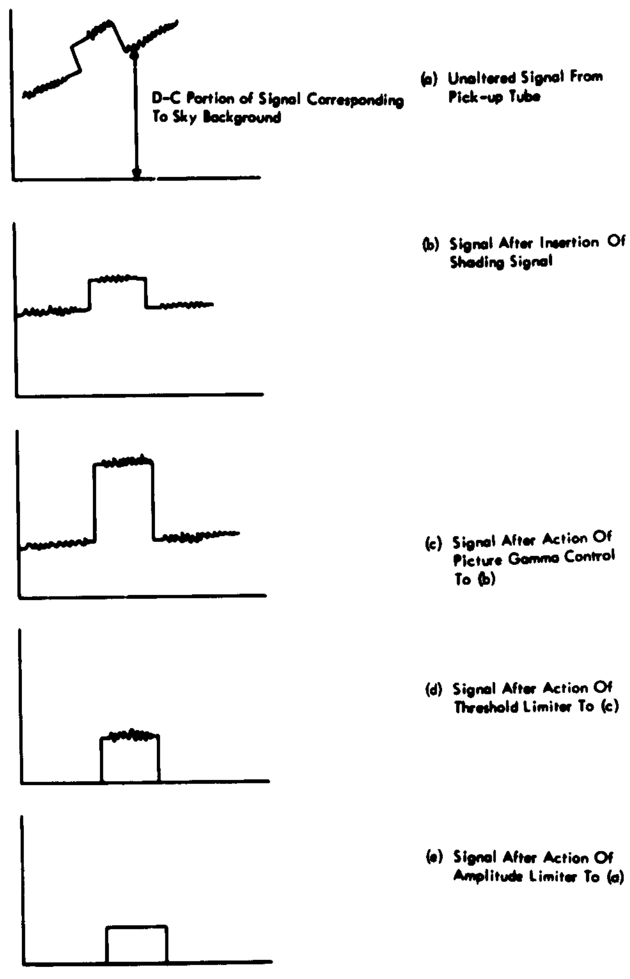

Figure 3-51. Methods of Background Suppression

3.2.5 Image Quality Analysis

3.2.5.1 Introduction

The purpose of the image quality analysis task for the image velocity sensor subsystem study is two-fold:

(1) To provide techniques for a detailed performance analysis of optical systems of the type required for IVSS;

(2) To support the trade-off analysis (Task 2) by applying these techniques to the various optical systems considered in the trade-off analysis.

In Section 3.2.5.2, the concept of modulation transfer is discussed. In Section 3.2.5.3 the modulation transfer analysis is applied to a specific optical system, consisting of a 36-inch, f/4.5 lens and Kodak 4404 emulsion. Section 3.2.5.4 describes a much more detailed computational technique that is capable of providing images of objects other than sinusoids. Section 3.2.5.5 summarizes the results obtained for several optical systems.

3.2.5.2 Modulation Transfer Analysis

A standard procedure for determining the fidelity with which an information processing system will reproduce the input is to put as nearly perfect representation of a precisely described impulse as possible into the system; then measure the degraded output. In the case of a photo-visual optical system designed for observation of surface objects from extreme altitudes, both atmospheric effects and vehicle motion are necessarily regarded as parts of the image processing system. When the input to such a system is a point of light, the output is called the photo-optical system spread function. From the mathematical and physical standpoint, working with the spatial domain (distance on the film) becomes unwieldy. Thus, this domain is generally transformed to the spatial frequency domain (the sum of the sine or cosine terms of different spatial frequencies into which the object can be decomposed). When a pulse (such as an ideal point of light) is the input to a system, the usual output will be different in both shape and amplitude. When the input is made up of sinusoids, however, only amplitude and phase changes are noted in the output. This is why sinusoids are generally used for routine analysis. The amplitude of the sinusoid components in the "degraded" output image plotted against spatial frequency produces a graph called the "transfer function" or "modulation transfer function."

The word "modulation" refers to the relationship between the transfer function and the loss of contrast between a ground target viewed by an ideal system and the target's photographic image recorded by a finite and imperfect system.

Contrast is defined as the ratio of the maximum to the minimum illuminance,

$$C = \frac{I_{max}}{I_{min}} ,$$

and the "modulation," M, is defined as

$$M = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = \frac{C - 1}{C + 1}$$

Thus, modulation values lie between 0 and 1.

The ratio of the image modulation, M_i, to object modulation, M_o, is the "modulation transfer function":

$$\frac{M_i}{M_o} = T.$$

This will be a function of spatial frequency because the ratio of modulation will be different for each component sinusoid. The modulation transfer function value at a particular frequency does not give the ratio of modulations for details of a size corresponding to the inverse of the spatial frequency, because every object in the scene is affected by the entire transfer function.

3.2.5.3 An Example of Modulation Transfer Analysis

For this example, a lens having a focal length of 36 inches and a speed of f/4.5 was used to expose Kodak 4404 film. Then, the resulting picture was examined to determine the resolution of the lens for a picture contrast ratio of 4:1. (A resolution of 1.33 seconds of arc, i.e. 167 lines/mm was required).

Figure 3-52 is the product of the modulation-transfer function for an f/4.5 system at 0.6 (60%) modulation for a target contrast of 4:1. Two lens transfer functions are shown: (1) an aperture-limited system, which is highly idealized; (2) a system with a wavefront disturbance equivalent to a $\lambda/2$ quadrature error. A wavefront distortion of this magnitude could easily be caused by the cumulative effect of normal optical shop practices in the assumed sequence of producing mirror surfaces and refractive element surfaces, plus the small but significant errors in aligning the optical elements. Itek has successfully designed, and by particularly careful quality control, consistently produced 24-inch, f/3.5 Petzval lenses that have modulation-transfer functions equivalent to a $\lambda/4$ error, when tested in the spectral region for which they are designed using Wratten No. 12 filters. In Figure 3 - 52 the intersection of the lens transfer function with the sloped line representing emulsion threshold indicates the over-all lens-film resolution for a system with an insignificant amount of uncompensated

image motion during exposure. Thus, the system requires something better than λ/2 quality optics, but does not demand perfection.

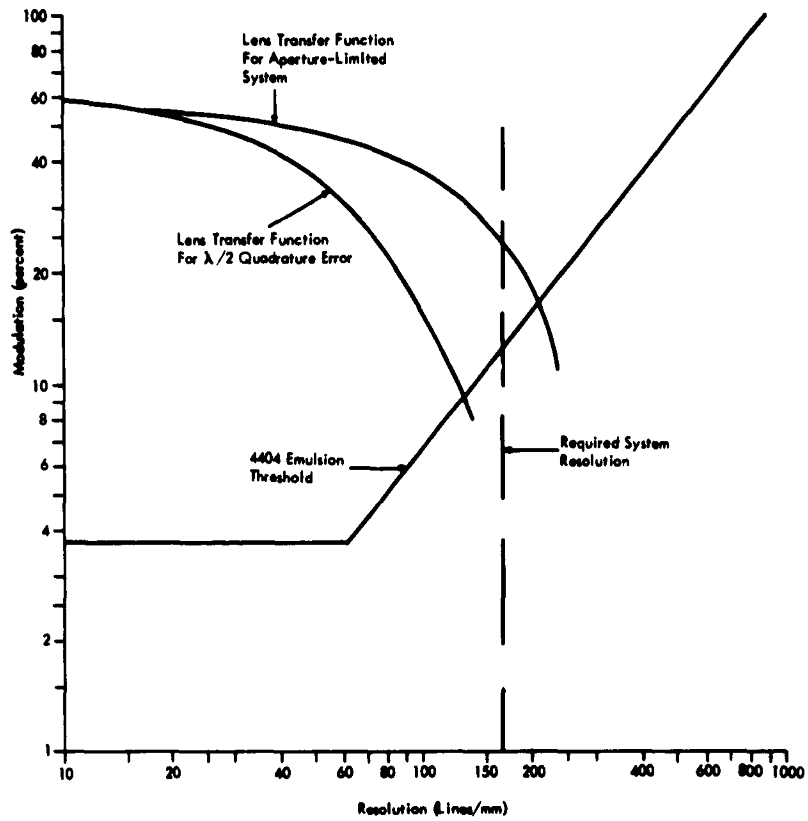

Figure 3-52. Static Performance of 36-in, F/4.5 Lens and Kodak 4404 Film

Figures 3-53 and 3-54 show the predicted system acuity when image motion is present. Figure 3-53 is the idealized aperture-limited system; Figure 3-54 is the other extreme, a system with a λ/2 error. For the anticipated range of motion during exposure, when the target illumination is 1000 foot-lamberts, the two figures show that the system is not motion limited. Consequently, improved fine-grain emulsions (expected to be available by the time the IVSS is operational) could be examined, and this could significantly increase the system resolution capabilities.

The above state-of-the-art considerations were paralleled by more detailed analyses by the staff and computer facilities at Itek. The results of these analyses are contained in Section 3.2.5.5.

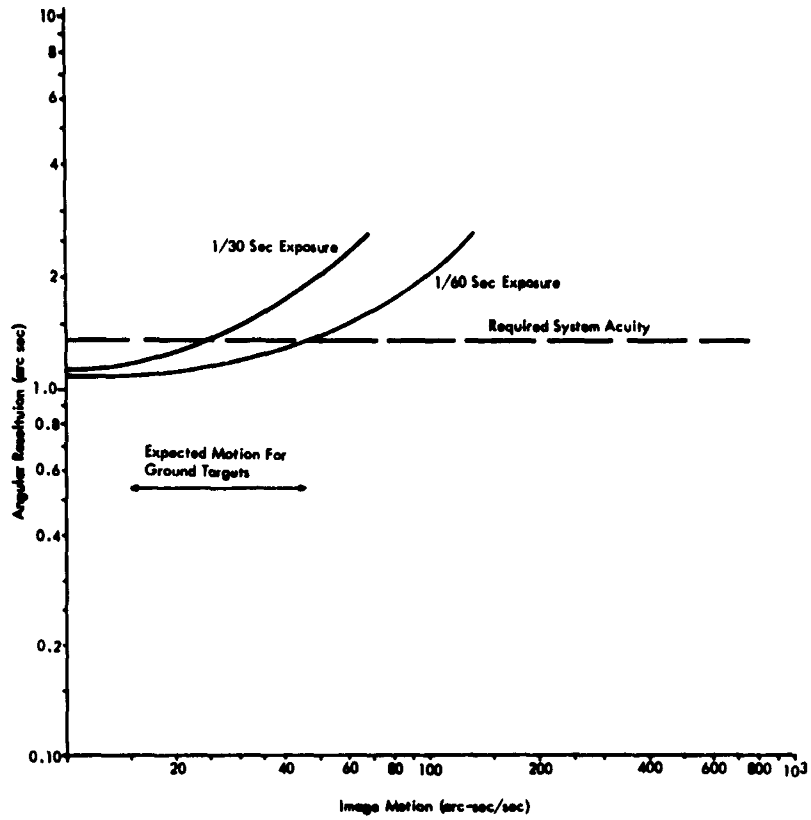

Figure 3-53. Performance of 24-inch f/4.5 Aperture-Limited Lens Using Kodak 4404 Film

3.2.5.4 Image Evaluation Methods Used by Itek

The purpose of this portion of the IVSS project was to predict the performance of a specified lens system under certain given operational conditions, using precise numerical methods. Specifically, given a certain lens, film and image motion, find the resolution of the system and describe the image of some particular objects.

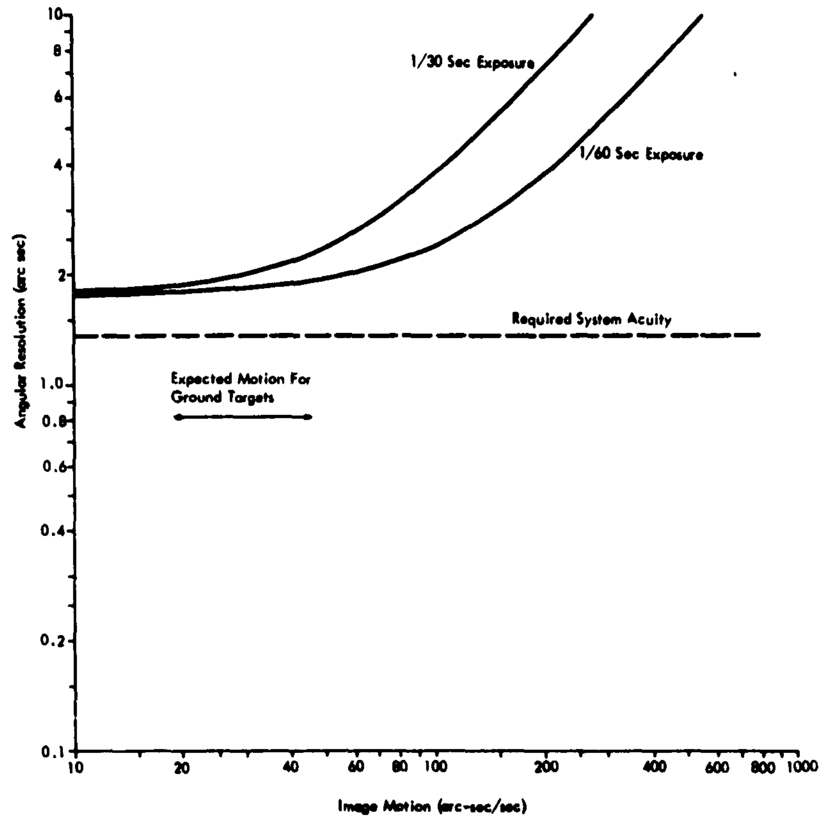

Figure 3-54. Performance of 24-inch, f/4.5 Lens with $\lambda/2$ Aberration Using Kodak 4404 Film

First, the optical system analysis determines how certain spatial frequencies pass through the system. For example, a sine wave having a known amplitude and spatial frequency is used as an object for comparing the amplitude and phase shift of its image. This is done for many frequencies to produce a complex function F(N) of spatial frequency (N) for the system. F(N) is given by

$$F(N) = A(N)\, e^{i\,\phi(N)},$$

where A(N) is the amplitude factor, or $\frac{A_{out}(N)}{A_{in}(N)}$, ϕ (N) is the phase shift, or $\phi\ out^{(N)} - \phi\ in^{(N)}$.

The spatial frequency function is determined for each component of the system; then combined as follows to give the corresponding function for the entire system:

$$F(N) = F_1(N)F_2(N)\ldots F_n(N)$$
$$= A_1(N)A_2(N)\ldots A_n(N)e^{i\left[\phi_1(N) + \phi_2(N) + \ldots \phi_n(N)\right]}$$
$$= A(N)e^{i\phi(N)}.$$

Or in words, the final amplitude factor is the product of the individual amplitude factors, and the final phase factor is the sum of the individual phase factors.

The analysis proceeds by breaking up the object into its sinusoidal constituents, which exhibit various frequencies and amplitudes, using the Fourier transform of the signal. These sine waves are then passed through the optical system and the resulting sine waves recombined to form the image. The Fourier transform provides conversion from coordinate space into frequency space; taking the inverse gets back to coordinate space. This provides the procedure for solving the problem:

(1) Determine the frequency response of the system.

(2) Take the Fourier transform of the object to get the object spectrum.

(3) Multiply the Fourier transform by the frequency response of the system to find the image spectrum.

(4) Take the inverse Fourier transform to produce the image.

The frequency response of the system and its components is often called the modulation transfer function (MTF). Once the frequency response of the system is known, the procedure follows easily. This procedure has been programmed by the Itek staff for the CDC-924 computer. This program (called POMP) consists of three parts: (1) taking the Fourier transform of the object, (2) multiplying frequency responses by the transform, and (3) taking the inverse transform to get the image. The resolution of the system depends only on the system frequency response.

The main analytical problem is to find the modulation transfer functions of the components of the system, particularly of the lens. This very long, difficult computation has been programmed by Itek for their CDC-924 computer.

The Itek program (called FREQ) computes the modulation transfer function of the lens over a given wavelength interval using the aberration coefficients (up to and including third-order spherical aberration) for three different wavelengths. This program first calculates the frequency

cutoff of the lens: $\omega_0 = \frac{1}{\lambda F}$, where λ is the mean wavelength in the interval over which the MTF is desired, and F is the speed of the lens. The program next plots the amplitude factor (contrast) versus wavelength in the given interval for spatial frequencies of $0.1\,\omega_0$, $0.2\,\omega_0$, $0.3\,\omega_0$, etc., for different focal shifts. Then the contrast is averaged over the wavelength interval by taking the area under the different curves ($0.1\omega_0$, $0.2\,\omega_0$, etc.) and dividing by the wavelength interval. This is the integrated contrast, which the program arranges in tabular form. Three different filters can be inserted in this averaging process by the use of their sensitivity curves in the wavelength range.

Thus, the output of FREQ consists of five parts for each focal shift. The first is the plot of contrast versus wavelength for the different spatial frequencies. The next four parts consist of the four integrated contrast tables corresponding to three with filters and one with no filter. This last table especially depends upon the wavelength interval chosen. To get the best results here, the wavelength interval should correspond to the wavelength range for which the lens is designed.

As an example, using the 24-inch, f/3.5 Petzval lens and the integrated contrast for a frequency of 100 lines/mm, for a wavelength range of 0.4 to 0.7 micron, the integrated contrast is 0.304. From the tables corresponding to the Wratten No. 21 filter and Kodak 4404 film, the values are 0.354 and 0.346, respectively. This filter has its low wavelength cutoff at 0.54 micron and transmits beyond 0.7 micron.

The modulation transfer function for Kodak 4404 film is determined experimentally, and the MTF for the image motion is calculated from the formula $F(N) = \frac{\sin \pi N \Delta}{\pi N \Delta}$, where Δ is the image blur during exposure.

The procedure can be demonstrated by following through a calculation, step-by-step, using a three bar target of 100 lines/mm as an object. For the example, use the proposed 36-inch, f/4.5 Petzval lens. The modulation transfer function of this lens was computed by FREQ, and can be seen in Figure 3-55. The MTF for Kodak 4404 film is shown in Figure 3-56, and the transfer function corresponding to an image motion (or image blur) of 0.726 and 2.166 microns can be seen in Figure 3-57. The frequency response of this system, which was computed by POMP, is the product of the individual frequency responses, and is illustrated by Figure 3-58. The point where the frequency response curve crosses the 0.04 modulation line determines the resolution of the system, assuming high contrast of the object. The 0.04 modulation line represents the minimum modulation that can be detected on this film.

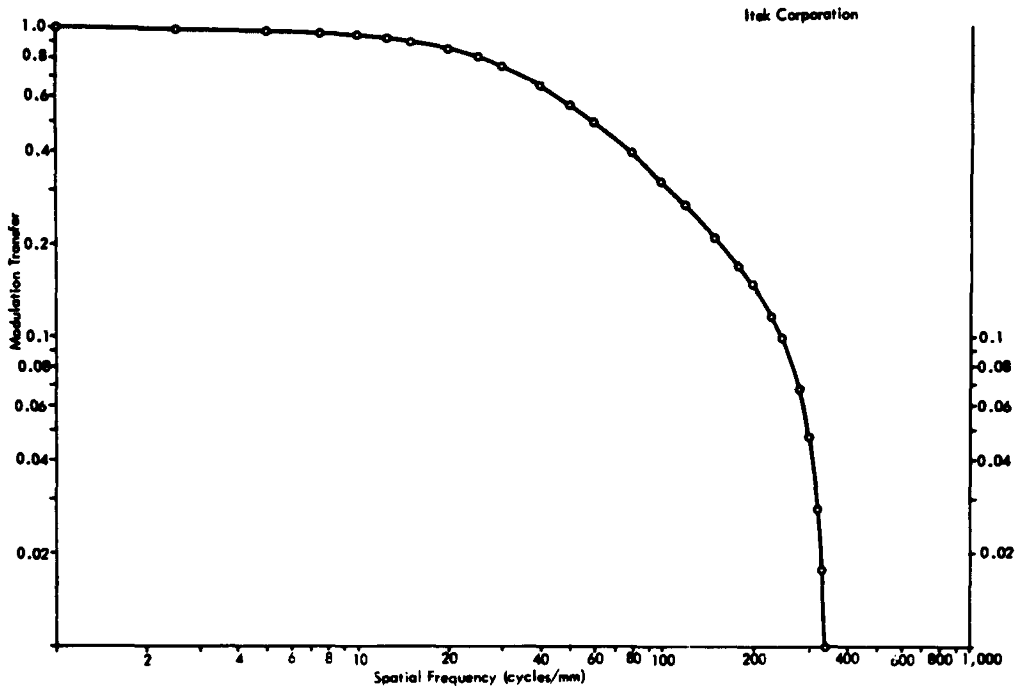

Figure 3-55. Transfer Function for a 36-inch, f/4.5 Petzval Lens, Using a Wratten No. 21 Filter

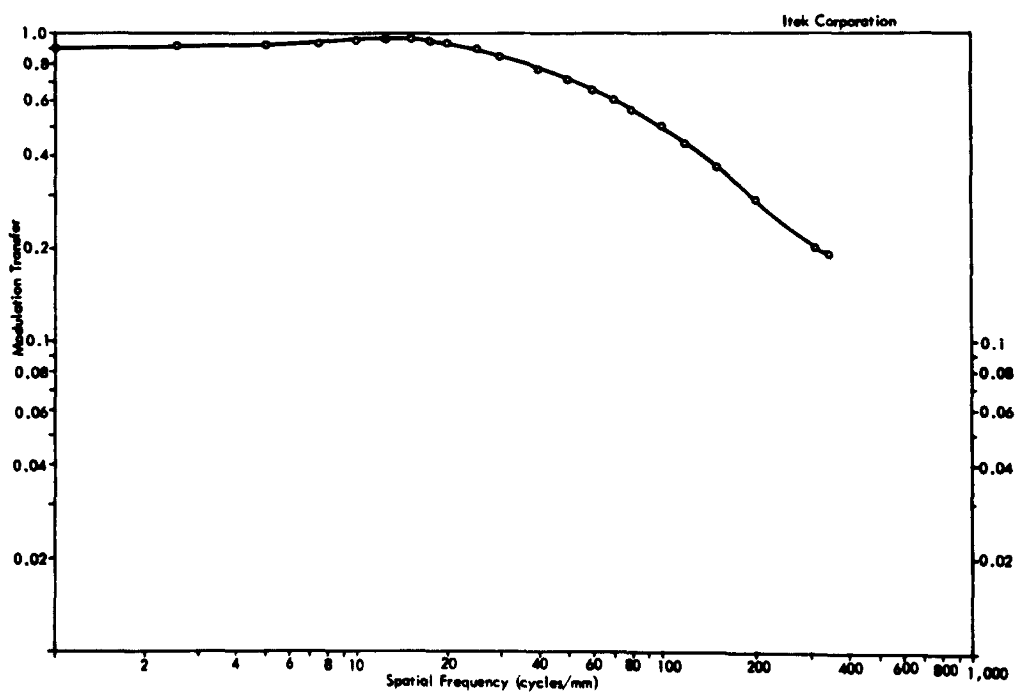

Figure 3-56. Transfer Function for Kodak 4404 Film

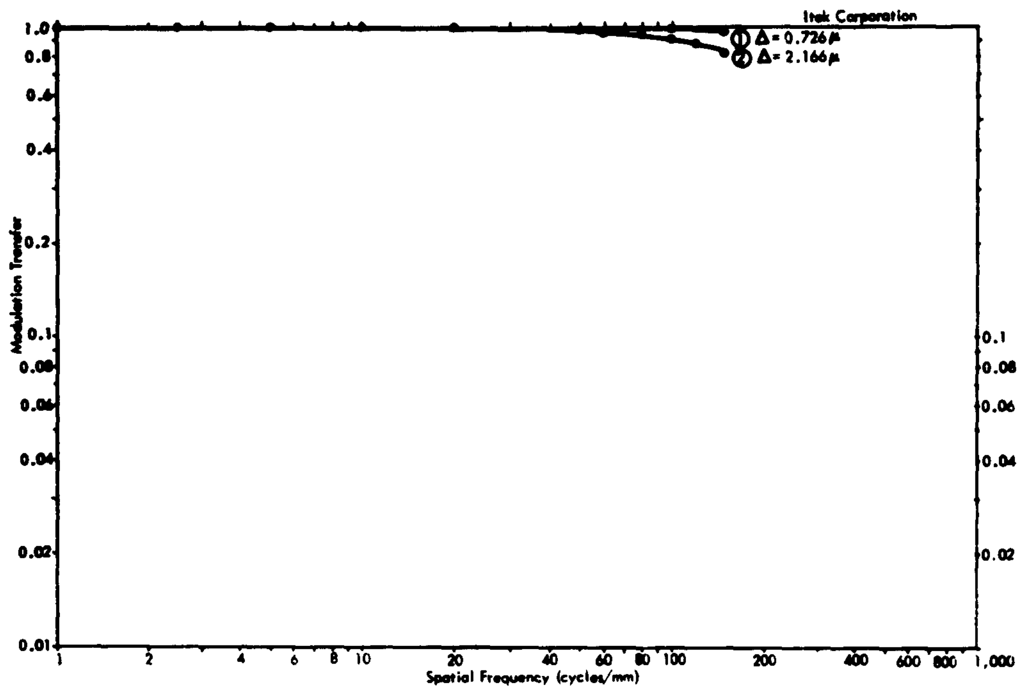

Figure 3-57. Image Motion Transfer Function

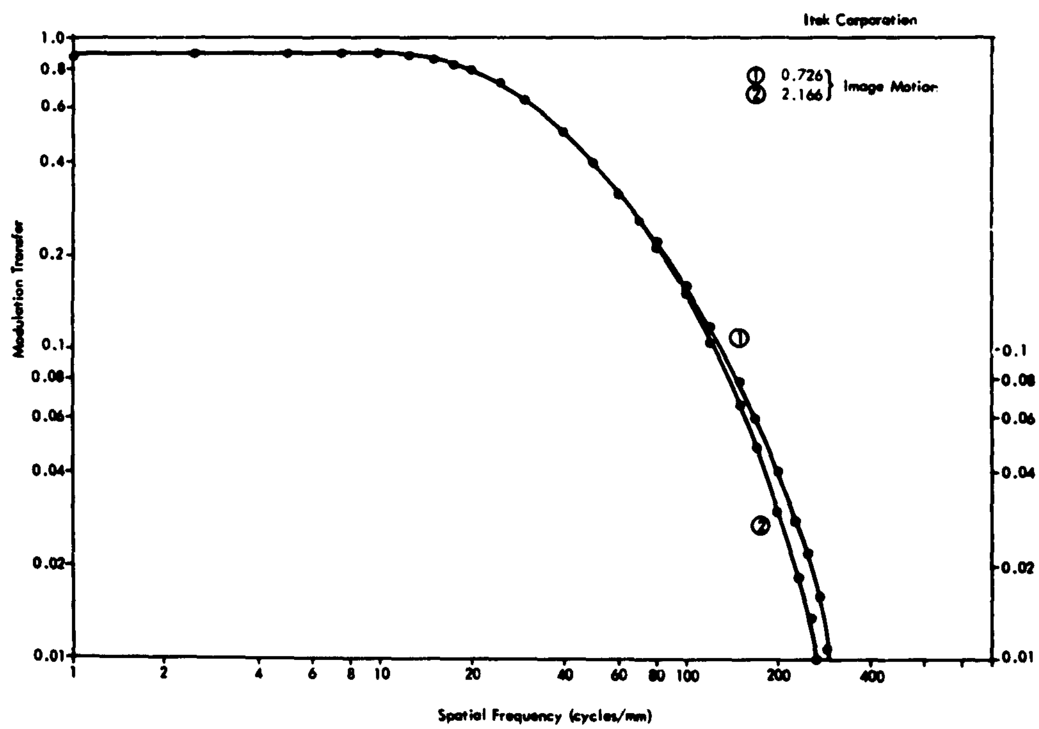

Figure 3-58. Total System Transfer Functions

This minimum modulation was determined experimentally. Assuming a 4:1 object contrast (0.6 modulation), the resolution of the system is taken where the curve crosses the line corresponding to a modulation of 0.04/0.6 = 0.067. These resolutions are tabulated below:

Image Motion (microns)	Resolution (lines/mm)	
	High Contrast	4:1 Contrast
0.766	200	160
2.166	180	150

Figure 3-59 shows the computed image of a three bar target of 100 lines/mm, and the object. Image motion apparently does not affect the image curve.

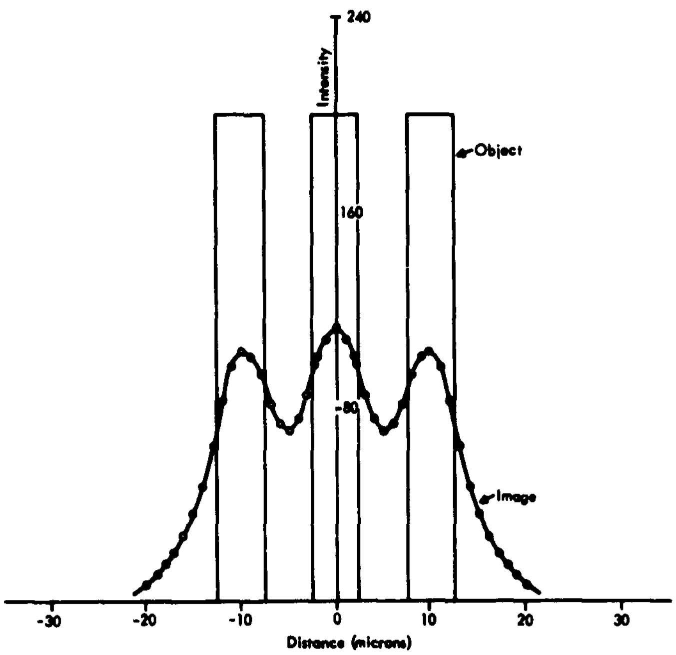

Figure 3-59. Object and Computed Image for the Total System

3.2.5.5 Summary of Image Quality Predictions

Table 3-9 provides a brief comparison of the results expected from several lens systems considered for IVSS. The reference conditions are:

- 4:1 contrast
- System light transmission of 0.37
- Kodak 4404 film
- Image density of 0.5 above fog

Table 3-9.

SUMMARY OF PREDICTED IMAGE QUALITY

Lens		Predicted Resolution (lines/mm, sec of arc)			
		Residual Image Motion:			
		15 sec of arc/sec		45 sec of arc/sec	
		Filter:		Filter:	
Focal Length (inches)	Speed	None	Wratten No.21	None	Wratten No. 21
13	f/3.5		170, 3.6		170, 3.6
24	f/3.5	180, 1.8	205, 1.6	180, 1.8	205, 1.6
34	f/5		170, 1.4		145, 1.6
36	f/4.5		175, 1.3		160, 1.4
66	f/5	92, 1.3	107, 1.1		84, 1.4

3.3 PTS Tracker

3.3.1 Requirements

The tracking servo system drives the scanning mirrors used to acquire and track ground and space targets. A two-gimbal system (pitch and roll) is driven by a digital interface in the primary mode, the outer gimbal being roll and the inner gimbal, pitch.

Because of the vehicle's orientation during tracking, the roll servo must drive the largest mass, but the pitch servo is subject to the largest accelerations and velocities and therefore presents the most stringent design characteristics. Thus, only the pitch servo will be discussed in detail; the roll servo will be functionally equivalent.

The maximum angular rate error of better than 0.2 percent should be satisfied for obliquity angles of ±45 degrees in order to maintain reasonable values of coverage and tracking times for out-of-plane ground targets. Analytic digital simulations described in Section 3.4 and other studies* have indicated a design goal of 10 arc seconds of PTS pointing error which would allow IMC's down to below 0.05 percent to be attained. The requirement for gimbal drive smoothness is derived from the need to obtain high-quality verification photographs (on the order of 5 feet of resolution). For vibration frequencies on the order of one per time exposure and higher, the smoothness requirement relates to an amplitude requirement (0.3 arc second) above which will result in excessive photographic blur. At lower frequencies, the vibration produces essentially a linear image motion in which allowable rate is a requirement. As pointed out below, the optical design was predicated on the assumption of 45 arc/seconds/second image motion. The servo, in order to contribute a negligible amount of this total error, is then required to insure that the error response does not exceed a maximum rate of 15 arc seconds/second.

The summary of the tracking servo requirements is listed in Table 3-10.

3.3.2 Load Parameters

Typical scanning mirror load characteristics used for this report are:

Inertia	5 inch-round seconds^2
Coulomb Friction	2 inch-rounds

Six methods of implementing the pitch scanning mirror servo were investigated. Functional operation of these circuits is explained below, including the applicable functional diagrams. Table 3-11 is a summary

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* TOR-269(4107-40)-7, Application of the Wiener Kalman Filter to MOL Manned Tracking, J. E. Lesinski, Aerospace Corporation, August 1964 (Confidential)

Table 3-10
SUMMARY OF TRACKING SERVO REQUIREMENTS (3 Sigma)

• Maximum Dynamic Pointing Accuracy	
(1) Terrestrial Targets	±10 arc seconds
(2) Fly-By Space Targets	±30 arc seconds
• Maximum Angular Rate	
(1) Terrestrial Targets (100-n mi altitude)	2.5 degrees/second
(2) Fly-By Space Targets (10-n mi)	33.5 degrees/second
• Maximum Angular Accelerations	
(1) Terrestrial Targets (100-n mi altitude)	0.07 degrees/second^2
(2) Fly-By Space Targets (10 n mi)	12.6 degrees/second^2
• Maximum Angular Rate Error 0.05 percent of θ @ θ = Fix 45 degrees (200-n mi altitude)	2.5 arc seconds/second
• Maximum Slope of Error Response*	15 arc seconds/second
• Maximum High Frequency Vibration Amplitude (f > 50 cps)	1.0 arc second

For digital position servo mode only.

of the weight, volume, and power requirements of the different primary scanning configurations.

3.3.3 Model 1 (Figure 3-60)

The pitch rate command is generated in the digital computer and added to the precomputed pitch rate error. This sum is then added with signals originating in the digital hand control and the rate feedback from the encoder to form the digital computer output. Hand-control signals are initiated by the operator whenever it is necessary to correct the computed pitch rate.

The computer output, which is the error of the closed loop, is converted to analog form and passed through the compensating network, which regulates the system gain and phase response for the required steady-state error and the degree of stability. The amplifier supplies the voltage and power gain needed to drive the d-c torque motor, which in turn drives the scanning mirror and encoder. The shaft encoder is fed back to close the loop, representing rate and position of the scanning mirror.

Table 3-11
WEIGHT, VOLUME, AND POWER - PITCH GIMBAL ONLY

Model	Weight (lb)*		Volume (in^3)*		Power Requirements (watts) Peak		Power Requirements (watts) Average	
	EM**	E***	EM**	E***	EM**	E***	EM**	E***
1	16	2	479	47	31	150	31	30
1a	16	2	479	47	31	150	31	30
1b	16	2	479	82	31	153	31	33
2	16	3	481	110	31	154	31	34
2a	16	4	481	216	31	161	31	41
2b	28	3	584	75	31	151	31	31
2b'****	86	3	1099	75	31	151	31	31

* Not including scanning mirror.
**EM - electromechanical
***E - electrical
**** 2b is a degraded mode of operation. If a tachometer is employed and the requirements are to be met, 2b' is the estimated trade-off parameter.

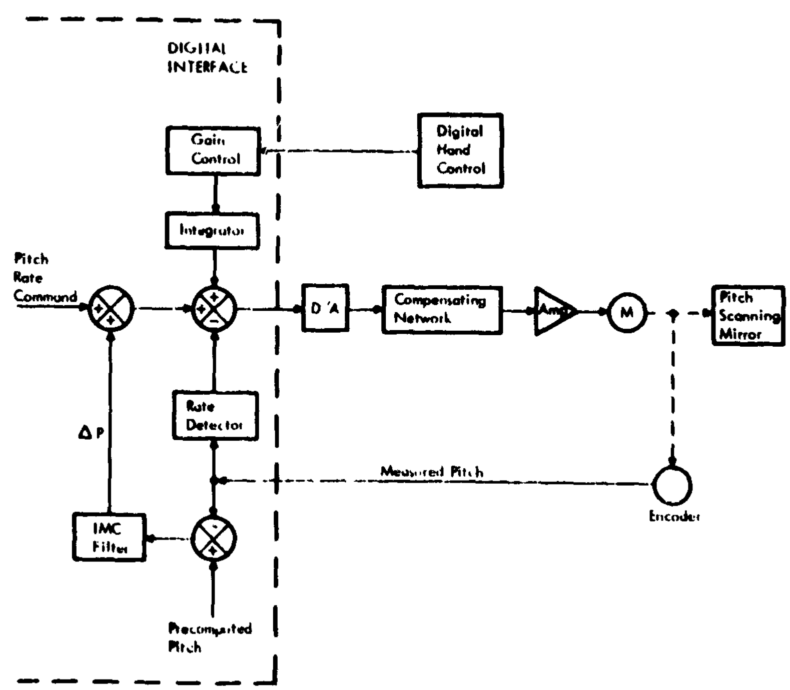


Figure 3-60. Model 1 Rate Servo - Digital Computer

3.3.4 Model 1a (Figure 3-61)

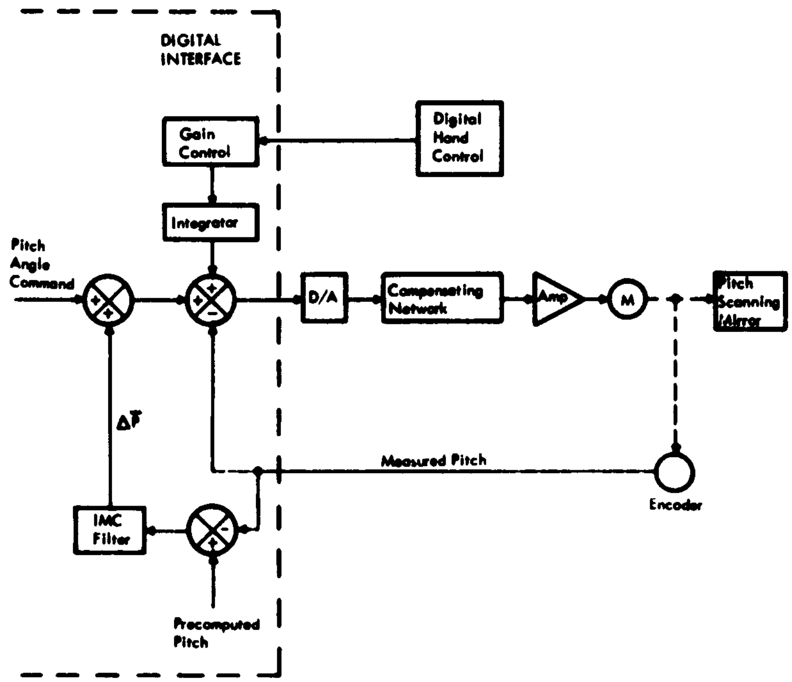


Figure 3-61. Model 1a Position Servo - Digital Computer

3.3.5 Model 1b (Figure 3-62)

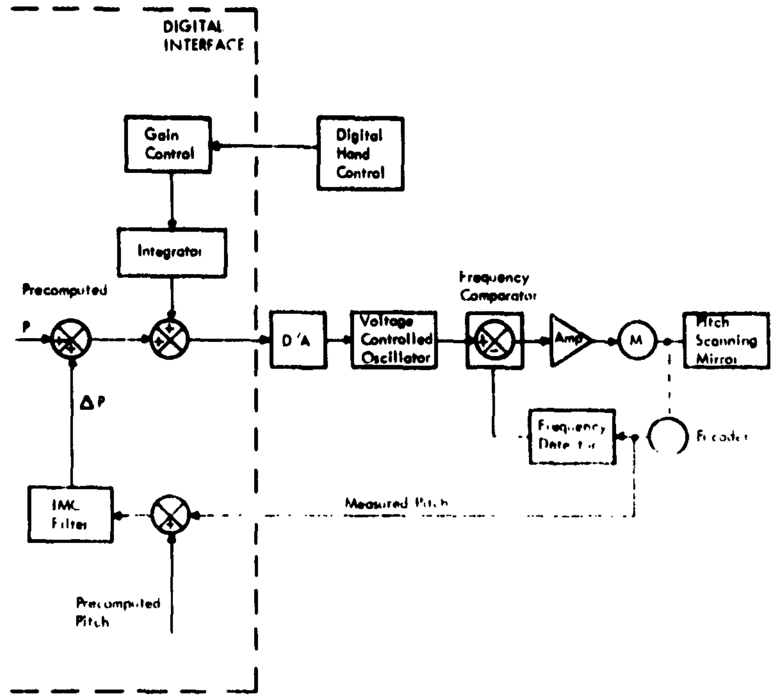


Figure 3-62. Model 1b Rate Servo - Digital Computer

The difference between precomputed pitch rate and pitch rate error is summed with the hand control signal and converted to analog form. The amplitude of the latter voltage sets the frequency of the voltage-controlled oscillator, whose output is compared with the frequency of the encoder's least significant bit. Any difference in frequency is detected by the frequency comparator, whose output drives the d-c motor through the amplifier. The actual pitch angle measured by the encoder is compared in the digital computer with the precomputed pitch angle, the filter output being the pitch rate error.

Present frequency comparison techniques can guarantee absolute frequency tracking by employing coarse and fine controls. The coarse control employs frequency measurement, and the fine control employs phase locking.

3.3.6 Model 2 (Figure 3-63)

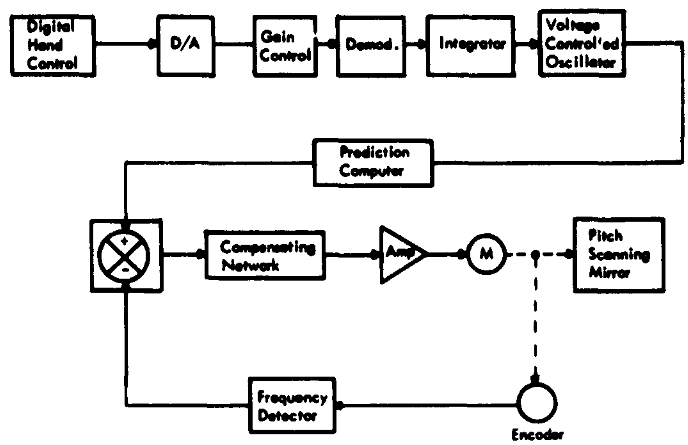


Figure 3-63. Model 2 Rate Servo - Analog Computer

The hand-control output is converted to an a-c voltage, multiplied by a variable gain, demodulated, and integrated. The amplitude of the integrator output controls the frequency of the voltage-controlled oscillator. This frequency is compared with the frequency derived from the encoder and the output of the prediction computer, any difference results in a voltage that drives the scanning mirror at a rate that nulls the image motion. The prediction computer anticipates where the operator intends to position the scanning mirror, thus preventing large overshoots.

3.3.7 Model 2a (Figure 3-64)

The hand-control voltage is modified by a gain term, integrated, and reconverted to a digital signal. This signal is compared to the digital outputs of the rate detector and prediction computer, converted to analog form, and drives the scanning mirror to null image motion.

3.3.8 Model 2b (Figure 3-65)

The hand-control output is modified by a variable gain, integrated, then summed with the outputs of the tachometer and the prediction computer. The sum voltage drives the tachometer, encoder, and scanning mirror at the rate determined by the operator. The d-c tachometer is directly coupled to the motor and has high voltage sensitivity to insure stability and accuracy.

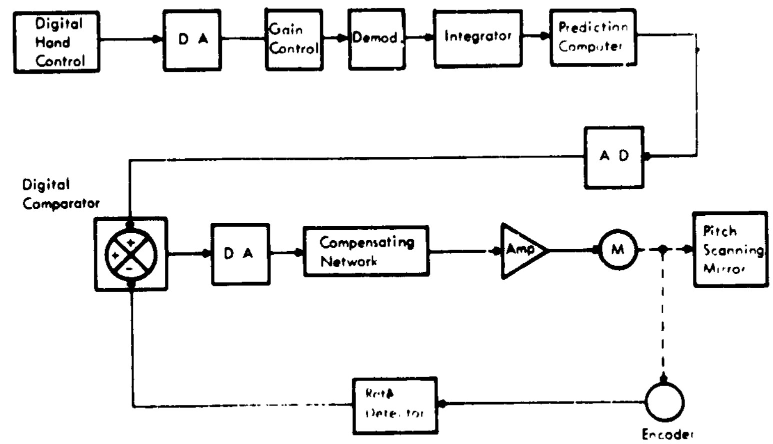


Figure 3-64. Model 2a Rate Servo - Analog Computer

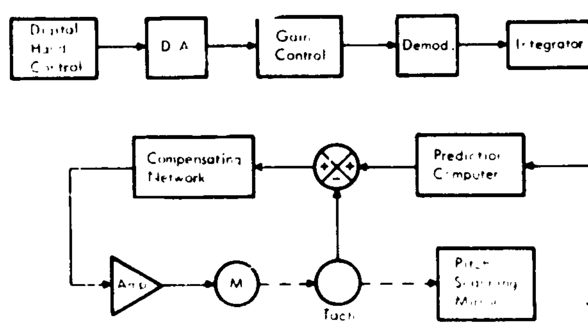


Figure 3-65. Model 2b Rate Servo · Analog Computer

3.3.9 Other IVSS Servos (See Figure 3-66)

3.3.9.1 Acquisition Pitch and Roll Scanning Mirror Servos

Synchro control transmitters are positioned by the pitch and roll scanning mirror servos and transmit shaft position information to synchro control transformers. The error voltage output of the control transformers is demodulated, amplified, and applied to the d-c torque motor, which drives the rotor of the control transformer until the error voltage is nulled. At this time, the acquisition pitch and roll shaft positions coincide with tracking pitch and roll shaft positions to within 10 minutes. Further studies are

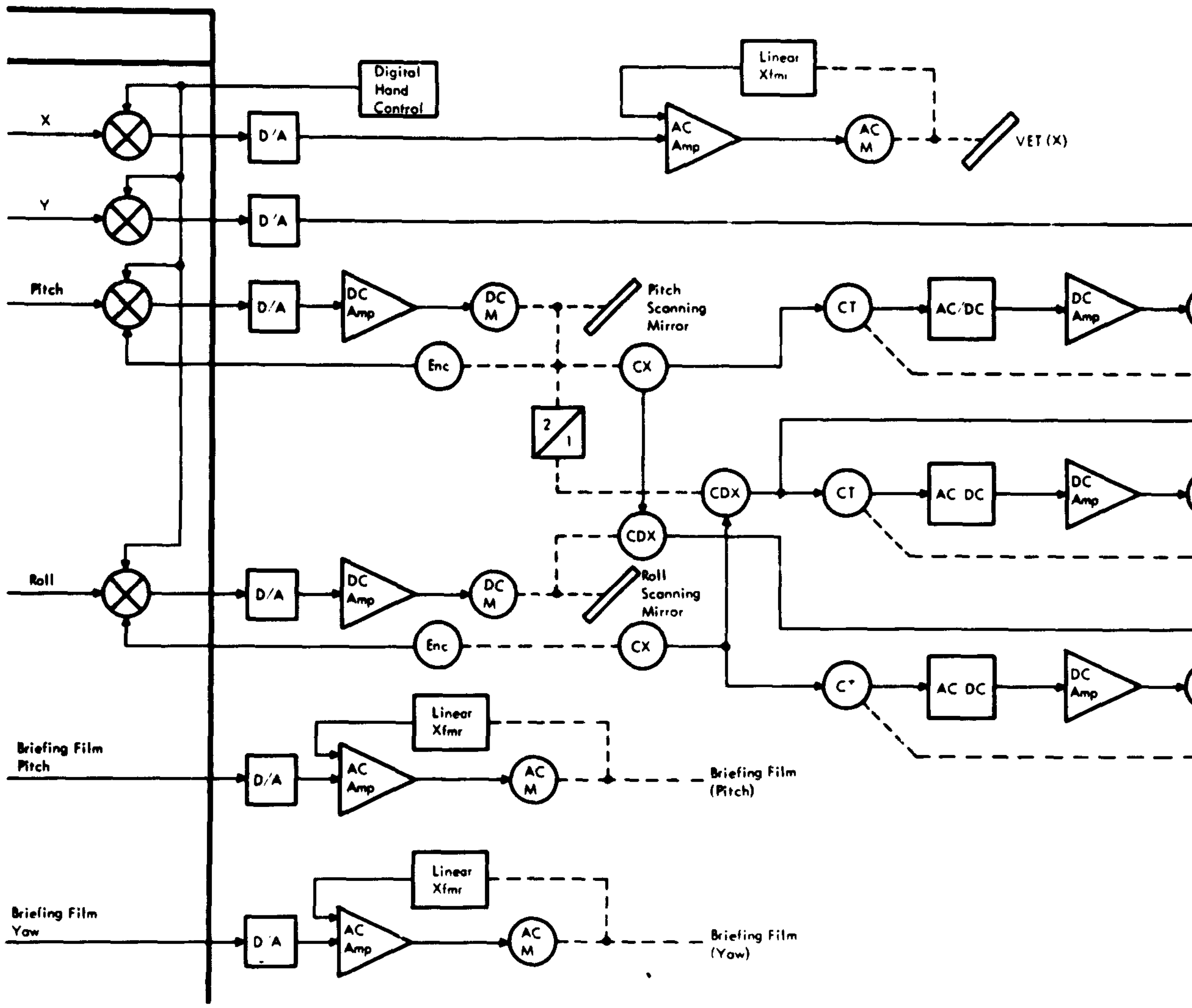
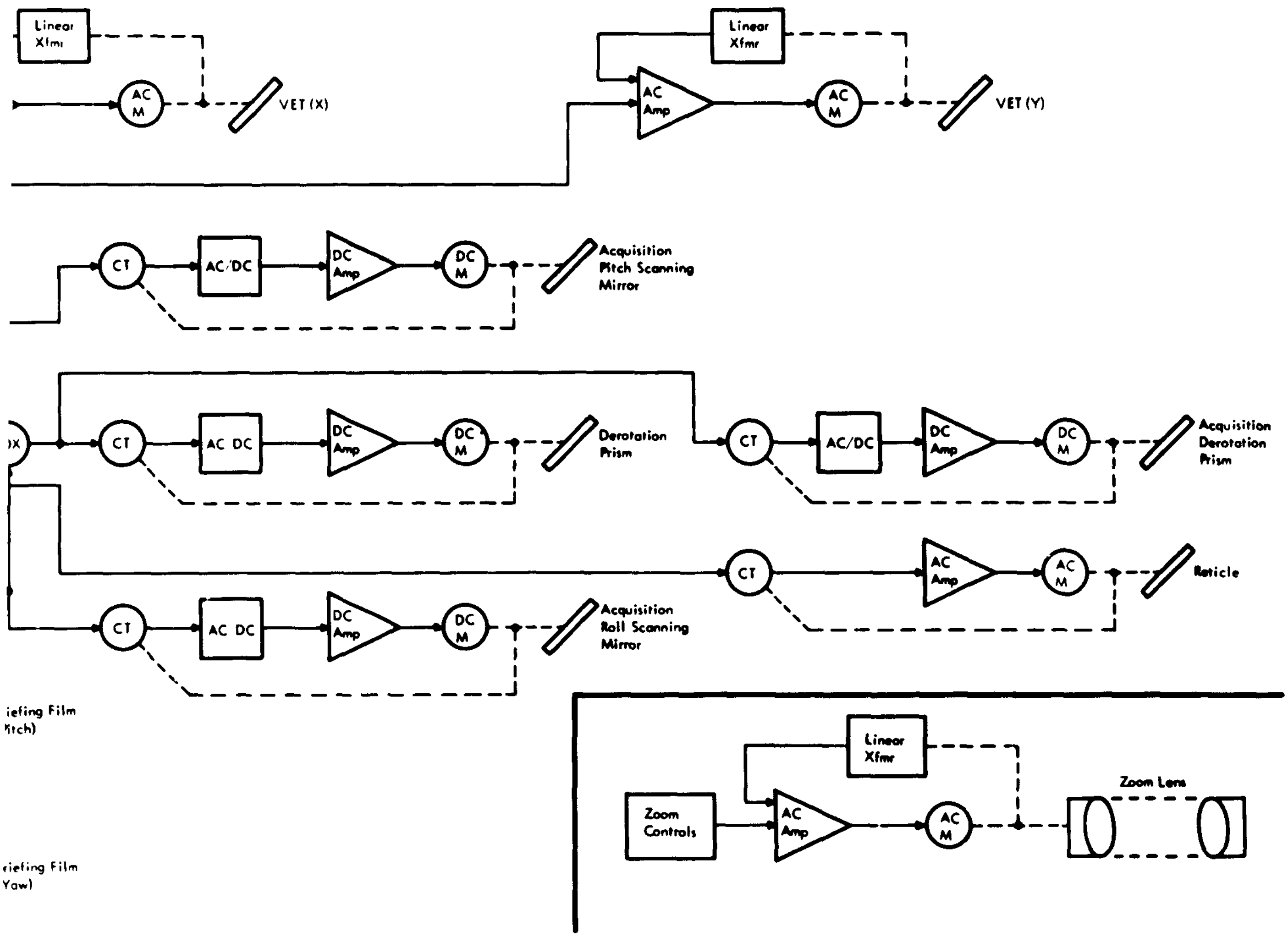


Figure 3-66. IVSS Servo Functional Schematic



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required to determine whether these servos should be operated independently in the event the PTS tracker servos malfunction.

3.3.9.2 Derotation Servos

The derotation angle ϕ_d is determined by $\phi_d = 0.5\,p + r$, where p is the pitch angle and r the roll angle. This is implemented by positioning the rotor of a synchro differential transmitter through a 2:1 gear reduction from the pitch shaft and feeding the stator from the synchro transmitter mounted on the roll shaft. The output of the synchro differential goes to both the derotation and acquisition derotation servos, which drive the derotation prisms to within 1 degree.

3.3.9.3 Visual Evaluation Tracker (VET) Servos (X and Y)

The hand-control signals originated by the operator are transformed into X and Y coordinates and added to pre-programmed signals in the computer. The sum (or difference) of these signals is converted to analog voltages and drives the X and Y servos accordingly. The feedback element is an induction potentiometer, which provides an accurate, linear indication of shaft rotation about the reference position up to plus or minus 90 degrees.

3.3.9.4 Briefing Film Pitch and Yaw Servos and Zoom Servo

These servos operate functionally as the VET servos, the only difference being in the implementation of their inputs.

3.3.9.5 Recticle Drive Servos

The synchro transmitter mounted on the pitch scanning mirror shaft transmits electrical shaft position information to the synchro differential driven by the roll scanning mirror shaft, the output of the latter being the sum of pitch and roll. This voltage is applied to the control transformer, whose error signal output drives the a-c motor until the error is zero, the recticle then being positioned in pitch plus roll.

3.4 Data Filtering Concepts as an Aid to Tracking

Earth Sighting Simulation results show man can attain 0.05 percent of the line of sight (LOS) angular rate provided he is given the proper equipment. Further decrease may be possible through further training. Another possibility for improvement would be to update some or all of the orbital parameters, body rates or attitude angles using a differential correction technique.

In order to extend the time interval for accurate open loop operation after cessation of manual control, to within reasonable limits for evaluation purposes, it appears that a differential correction (updating) technique may be desirable. The purpose of this section is then to present the salient feature of an analysis directed towards the utilization of a Weiner-Kalman filter for estimating certain IMC-sensitive parameters.

The following sections describe some of the analytical work performed in formulating the system dynamics. The sensitivities of the IMC to errors in the state variables are given.

Alternate filter configurations are then discussed, followed by a presentation of the numerical results obtained from one differential correction technique that was available for extensive digital simulation.

3.4.1 System Dynamics

The analysis in this section considers the problem of tracking a known landmark from an orbiting satellite. Specifically the area of interest is the utilization of the pitch and roll angles of the line of sight, (LOS) relative to the vehicle to improve the estimate of the state variables. The updated values of the state variables are then used to furnish an updated value of the desired pitch and roll rates of the LOS.

Insight into the problem may be obtained by considering the following formulation as one of many possible implementations.

The pitch, (θ), and roll, (ϕ), angles of the LOS are given by (Figure 3-67)

$$\sin \theta = \vec{e}_p \cdot \vec{i}_v \tag{3-20}$$

$$\tan \phi = \frac{\vec{e}_p \cdot \vec{k}_v}{\vec{e}_p \cdot \vec{j}_v} \tag{3-21}$$

where $\vec{e}_p$ is a unit vector in the direction of the line of sight; ($\vec{i}_v$, $\vec{j}_v$, $\vec{k}_v$) are a unit triad fixed in the vehicle; $\vec{i}_v$ is along the roll axis; $\vec{j}_v$ is directed toward the "keel"; and $\vec{k}_v$ completes the right handed system.

The range vector $\vec{p}$ satisfies the equation

$$\vec{r} + \vec{p} = \vec{r}_e \tag{3-22}$$

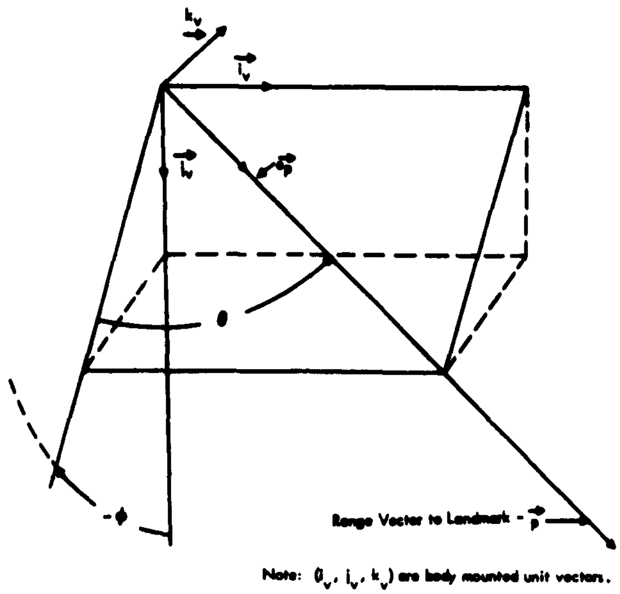

Figure 3-67. Pitch and Roll Angles of the Line of Sight

where $\vec{r}$ is the geocentric position vector of the satellite and $\vec{r}_e$ the geocentric position vector of the landmark. If the vector $\vec{r}_e$ is known, then the computation of ϕ and θ are dependent on a knowledge of $\vec{r}$ and the orientation of the vehicle. These quantities are however not precisely known at each instant of time. The differential correction technique consideration involves a linerization of the system dynamics about a reference trajectory.

The trajectory of the satellite in free fall satisfies the nonlinear homogeneous differential equation

$$\frac{d}{d_t}\left\{x\right\} = \left\{f(x)\right\} \tag{3-23}$$

where $\left\{x\right\}$ is a (6x1) column vector, x_1, x_2, x_3, being the components of position and x_4, x_5, x_6 the components of velocity. Let this vector be denoted as a nominal value plus a small perturbation i. e.,

$$\left\{x\right\} = \left\{x^N\right\} + \left\{\delta x\right\} \tag{3-24}$$

The linearized perturbation equations (sometimes called the variational equations) are

$$\frac{d}{d_t}\left\{\delta x(t)\right\} = \left[f(t)\right]\left\{\delta x(t)\right\} \tag{3-25}$$

where $[F(t)]$, the Jacobian of $\{f\}$, is a (6x6) matrix evaluated for values of $\{x^N\}$ on the nominal trajectory. The solution of (3-25) may be written as

$$\{\delta x(t)\} = [\phi(t;t_o)] \{\delta x(t_o)\} \tag{3-26}$$

where the 6x6 matrix $\phi(t;t_o)$ is often called the state transistion matrix. The integration of (3-25) may be done in closed form providing the two body potential (μ/r) is employed. Otherwise the state transition will have to be obtained via numerical integration. The employment of a numerical integration of the variational equations may be desirable even in the case of a "two body" approximation.

Euler's equations of motion of the rigid body (satellite) are

$$\left.\begin{aligned} I_1 \frac{d}{d_t} W_{xv} + (I_3 - I_2) W_{yv} W_{zv} &= N_{xv} \\ I_2 \frac{d}{d_t} W_{yv} + (I_1 - I_3) W_{xv} W_{zv} &= N_{yv} \\ I_3 \frac{d}{d_t} W_{zv} + (I_2 - I_1) W_{xv} W_{yv} &= N_{zv} \end{aligned}\right\} \tag{3-27}$$

where the xv yv zv axes are assumed to be principal axes. If the attitute control engines are off and the gravity gradient torques are neglected the monent vector vanishes. Furthermore it might be assumed that the xv, axis is an axis of symmetry. Then Euler's equations become

$$\left.\begin{aligned} \frac{d}{d_t} W_{xv} &= 0 \\ \frac{d}{d_t} W_{yv} &= \Delta I\, W_{xv} W_{zv} \\ \frac{d}{d_t} W_{zv} &= \Delta I\, W_{xv} W_{yv} \end{aligned}\right\} \tag{3-28}$$

where $\Delta I = \frac{I_1 - I_2}{I_3}$ The assumption that xv is an axis of symmetry simplifies the problem but is not required for a successful solution. Perturb the nonlinear Equation (3-28) to obtain

$$\frac{d}{d_t}\begin{Bmatrix} \delta W_{xv} \\ \delta W_{yv} \\ \delta W_{zv} \end{Bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ \Delta I W_{zv}{}^N & 0 & \Delta I W_{xv}{}^N \\ \Delta I W_{yv}{}^N & \Delta I W_{xv}{}^N & 0 \end{bmatrix} \begin{Bmatrix} \delta W_{xv} \\ \delta W_{yv} \\ \delta W_{zv} \end{Bmatrix}$$

where

$$\begin{Bmatrix} W_{xv} \\ W_{yv} \\ W_{zv} \end{Bmatrix} = \begin{Bmatrix} W^N_{xv} \\ W^N_{yv} \\ W^N_{zv} \end{Bmatrix} + \begin{Bmatrix} \delta W_{xv} \\ \delta W_{yv} \\ \delta W_{zv} \end{Bmatrix} \tag{3-29}$$

and $\{W^N\}$ are the nominal values of the body axis components of the angular velocity of the vehicle. The nominal values $\left\{W^N_{xv}\right\}$ satisfy (3-28). This implies that $\left\{W^N_{xv}\right\}$ may be obtained as an integration of

$$\frac{d}{d_t} W^N_{xv} = 0$$

$$\frac{d}{d_t} W^N_{yv} = \Delta I \, W^N_{xv} W^N_{zv}$$

$$\frac{d}{d_t} W^V_{zv} = \Delta I \, W^N_{xv} \; W^N_{yv} \tag{3-30}$$

in order that the square matrix in (3-29) may be determined as a function of time. Alternately, body-mounted gyro's could be used to furnish these values. Let the solution of (3-29) be denoted as

$$\left\{\delta W(t)\right\} = \left[\psi_1\left(t_1 t_o\right)\right] \left\{\delta W \;\left(t_o\right)\right\} \tag{3-31}$$

A knowledge of $\left\{W(t)\right\}$ must now be used to determine the attitude of the vehicle. One formulation of the problem would require the computation of the matrix of direction cosines $\left[A\right]$. This is the attitude matrix and is the transformation between inertial components and vehicle components i. e.,

$$\begin{Bmatrix} x_v \\ y_v \\ z_v \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{Bmatrix} x_I \\ y_I \\ z_I \end{Bmatrix} \tag{3-32}$$

The body rates may be employed to determine a set of Euler angles, i. e.,

$$\frac{d}{d_t} \begin{Bmatrix} \phi_v \\ \theta_v \\ \psi_v \end{Bmatrix} = \left[C\right] \begin{Bmatrix} W_{xv} \\ W_{yv} \\ W_{zv} \end{Bmatrix} = \left\{g(\phi_v, \theta_v, \psi_v)\right\} \tag{3-33}$$

where the elements of the matrix C are nonlinear functions of the Euler angles (ϕ_v, θ_v, ψ_v). PerturbEquation (3-33) to obtain

$$\frac{d}{d_t} \begin{Bmatrix} \delta\phi_v \\ \delta\theta_v \\ \delta\psi_v \end{Bmatrix} = \left[G(t)\right] \begin{Bmatrix} \delta\phi_v \\ \delta\theta_v \\ \delta\psi_v \end{Bmatrix} + \left[C\right] \begin{Bmatrix} \delta W_{xv} \\ \delta W_{yv} \\ \delta W_{zv} \end{Bmatrix} \tag{3-34}$$

where the 3x3 matrix, G(t) is the Jacobian of $\left\{g\right\}$ and is evaluated for the nominal or reference values ϕ^N_v, θ^N_v, ψ^N_v. Equations (3-29) and (3-34) could be combined into one vector matrix equation, e. g:

where the 3x3 matrix, G(t) is the Jacobian of $\{g\}$ and is evaluated for the nominal or reference values, ϕ_v^N, θ_v^N, ψ_v^N. Equations (3-29) and (3-34) could be conbined into one vector matrix equation, e.g:

$$\frac{d}{d_t}\begin{Bmatrix} \delta W_x \\ \delta W_y \\ \delta W_z \\ \delta\phi_v \\ \delta\theta_v \\ \delta\psi_v \end{Bmatrix} = \left[\begin{array}{ccc|c} 0 & 0 & 0 & \\ \Delta I\, W_{zv}^N & & \Delta I\, W_{xv}^N & [0] \\ \Delta I\, W_{yv}^N & \Delta I\, W_{zv}^N & 0 & \\ \hline & [G(t)] & & [C(t)] \end{array}\right]\begin{Bmatrix} \delta W_x(t) \\ \delta W_y(t) \\ \delta W_z(t) \\ \delta\phi_v(t) \\ \delta\theta_v(t) \\ \delta\psi_v(t) \end{Bmatrix} \tag{3-35}$$

where $[C(t)]$ is the matrix in Equation (3-33) evaluated for nominal values ϕ_v^N, θ_v^N, ψ_v^N.

The solution of Equation (3-33) may be denoted by

$$\begin{Bmatrix} \delta W_x(t) \\ \delta W_y(t) \\ \delta W_z(t) \\ \delta\phi_v(t) \\ \delta\theta_v(t) \\ \delta\psi_v(t) \end{Bmatrix} = \left[\begin{array}{c|c} [\psi_1(t_1 t_0)] & [0] \\ \hline [\psi_3(t_1 t_o)] & [\psi_4(t_1 t_0)] \end{array}\right]\begin{Bmatrix} \delta W_x(t_o) \\ \delta W_y(t_o) \\ \delta W_z(t_o) \\ \delta\phi_v(t_o) \\ \delta\theta_v(t_o) \\ \delta\psi_v(t_o) \end{Bmatrix} \tag{3-36}$$

or, in shorthand notation

$$\left\{\begin{array}{c} \delta W(t) \\ \hline \delta\phi(t) \end{array}\right\} = \left[\begin{array}{c|c} \psi_1 & 0 \\ \hline \psi_3 & \psi_4 \end{array}\right]\left\{\begin{array}{c} \delta W(t_o) \\ \hline \delta\phi_v(t_o) \end{array}\right\} \tag{3-37}$$

The elements of the transformation matrix A are nonlinear functions of ϕ_v, θ_v, ψ_v. An increment in an element of A is related to the increments in the Euler angles by:

$$\delta A_{ij} = \begin{bmatrix} \dfrac{\delta A_{ij}}{\delta\phi_v} & \dfrac{\delta A_{ij}}{\delta\theta_v} & \dfrac{\delta A_{ij}}{\delta\psi_v} \end{bmatrix}\begin{Bmatrix} \delta\phi_v \\ \delta\theta_v \\ \delta\phi_v \end{Bmatrix} \tag{3-38}$$

or

$$\begin{Bmatrix} \delta A_{11}(t) \\ \delta A_{12}(t) \\ \delta A_{13}(t) \end{Bmatrix} = [J_1]\begin{Bmatrix} \delta\phi_v(t) \\ \delta\theta_v(t) \\ \delta\psi_v(t) \end{Bmatrix} \tag{3-39}$$

where J_1 is a Jacobian, i.e. $\left[\dfrac{\delta(A_{11}, A_{12}, A_{13})}{\delta(\phi_v, \theta_v, \psi_v)}\right] = J_1$

Similarly

$$\begin{Bmatrix} \delta A_{21}(t) \\ \delta A_{22}(t) \\ \delta A_{23}(t) \end{Bmatrix} = [J_2] \begin{Bmatrix} \delta\phi_v(t) \\ \delta\theta_v(t) \\ \delta\psi_v(t) \end{Bmatrix} \tag{3-40}$$

and

$$\begin{Bmatrix} \delta A_{21}(t) \\ \delta A_{22}(t) \\ \delta A_{23}(t) \end{Bmatrix} = [J_3] \begin{Bmatrix} \delta\phi_v(t) \\ \delta\theta_v(t) \\ \delta\psi_v(t) \end{Bmatrix} \tag{3-41}$$

The pitch angles of the LOS relative to the vehicle is

$$\sin\theta = \vec{e}_p \cdot \vec{i}_v \tag{3-42}$$

The differential $\delta\theta$ is given by

$$\delta\theta = \left[\frac{-\cos}{p} \quad \frac{\cos\phi\sin\theta}{p} \quad \frac{\sin\phi\sin\theta}{p} \right] \left[A^T\right] \begin{Bmatrix} \delta_x \\ \delta_y \\ \delta_z \end{Bmatrix}$$

$$+ \left[\sin\theta \quad \cos\phi\cos\theta \quad \sin\phi\cos\theta \right] [A] \begin{Bmatrix} \delta A_{11} \\ \delta A_{12} \\ \delta A_{13} \end{Bmatrix} \tag{3-43}$$

since $\vec{i}_v = A_{11}\vec{i}_I + A_{12}\vec{j}_I + A_{13}\vec{k}_I$ where $\vec{i}_I$, $\vec{j}_I$, $\vec{k}_I$ is a unit inertial triad along x_I, y_I, z_I respectively.

Employing Equation (3-39) to obtain

$$\delta\theta = \underset{(1\text{x}3)}{\left[M_4\right]} \left\{\delta_x\right\} + \underset{(1\text{x}3)}{\left[0\right]} \left\{\delta W_x\right\} + \left[M_6\right] \left\{\delta\phi_v\right\} \tag{3-44}$$

$$\delta\theta \left[M_4 \;\middle|\; 0 \;\middle|\; M_6 \right] \begin{Bmatrix} \{\delta x_v\} \\ \{\delta W_x\} \\ \{\delta\phi_v\} \end{Bmatrix} \tag{3-45}$$

$$\text{where } M_4 = \left[\frac{-\cos\theta}{p} \quad \frac{\cos\phi\sin\theta}{p} \quad \frac{\sin\phi\sin\theta}{p} \right] \left[A^T\right] \tag{3-46}$$

$$M_6 = \left[\sin\theta \quad \cos\phi\cos\theta \quad \sin\phi\cos\theta \right] [A] \; [J_1] \tag{3-47}$$

The roll angle of the LOS relative to the vehicle is

$$\tan\theta = \frac{\vec{e}_p \cdot \vec{k}_v}{\vec{e}_p \cdot \vec{j}_v} \tag{3-48}$$

The differential of ϕ is

$$\delta\theta = \frac{1}{\cos\theta}\begin{bmatrix}0 & \frac{\sin\theta}{p} & \frac{-\cos\theta}{p}\end{bmatrix}\begin{Bmatrix}\delta x_v\\ \delta y_v\\ \delta z_v\end{Bmatrix}$$

$$+\frac{\cos\phi}{\cos\theta}\begin{bmatrix}\sin\theta & \cos\phi\ \cos\theta & \sin\phi\ \cos\theta\end{bmatrix}\begin{bmatrix}A\end{bmatrix}\begin{Bmatrix}\delta A_{31}\\ \delta A_{32}\\ \delta A_{33}\end{Bmatrix}$$

$$-\frac{\sin\phi}{\cos\theta}\begin{bmatrix}\sin\theta & \cos\phi\ \cos\theta & \sin\phi\ \cos\theta\end{bmatrix}\begin{bmatrix}A\end{bmatrix}\begin{Bmatrix}\delta A_{21}\\ \delta A_{22}\\ \delta A_{23}\end{Bmatrix} \quad (3\text{-}49)$$

Employ Equations (3-40), (3-41), and (3-32)

$$\delta\phi = \begin{bmatrix}M_1 & | & 0 & | & M_3\end{bmatrix}\begin{Bmatrix}\{\delta x\}\\ \{\delta W_x\}\\ \{\delta\phi_v\}\end{Bmatrix} \quad (3\text{-}50)$$

where

$$M_1 = \frac{1}{\cos\theta}\begin{bmatrix}0 & \frac{\sin\phi}{p} & -\frac{\cos\phi}{p}\end{bmatrix}\begin{bmatrix}A\end{bmatrix} \quad (3\text{-}51)$$

and

$$M_3 = \frac{\cos\phi}{\cos\theta}\begin{bmatrix}\sin\theta & \cos\phi\ \cos\theta & \sin\phi\ \sin\theta\end{bmatrix}\begin{bmatrix}A\end{bmatrix}\begin{bmatrix}J_3\end{bmatrix}$$

$$-\frac{\sin\phi}{\cos\theta}\begin{bmatrix}\sin\theta & \cos\phi\ \cos\theta & \sin\phi\ \sin\theta\end{bmatrix}\begin{bmatrix}A\end{bmatrix}\begin{bmatrix}J_2\end{bmatrix}$$

Combining Equations (3-44) and (3-50), we have (3-52)

$$\begin{Bmatrix}\delta\phi\\ \delta\theta\end{Bmatrix} = \begin{bmatrix}[M_1] & [0] & [M_3]\\ \hline [M_4] & [0] & [M_6]\end{bmatrix}\begin{Bmatrix}\{\delta x\}\\ \{\delta W_x\}\\ \{\delta\phi_v\}\end{Bmatrix} \quad (3\text{-}53)$$

Where the perturbed quantities on each side of Equation (3-53) are evaluated at time t. The (6x9) coefficient matrix in Equation (3-53)) is called the observation matrix.

The quantities $\delta\phi$ (t) and $\delta\theta$ (t) are obtained as measured values. The state vector on the right-hand side of Equation (3-53) is to be determined from observations (measurements). Obviously the problem is under determined for any value of $\delta\theta$ and $\delta\phi$. A series of measurements could be taken to over-determine the system, e.g:

$$\{\delta\ (t_1)\} = [M(t_1)]\ \{\delta\ (t_1)\}\ [M(t_1)]\ [\phi\ (t_1, t_o)]\{\delta(t_o)\}$$

$$\{\delta\ (t_v)\} = [M(t_v)]\ [\phi\ (t_2, t_o)]\ \{\delta\ (t_o)\} \quad (3\text{-}54)$$

$$\{\delta\ (t_w)\} = [M(t_k)]\ [\phi\ (t_k, t_o)]\ \{\delta\ (t_o)\}$$

where the matrix

$$\Phi(t_1 t_o) = \left[\begin{array}{c|c|c} \underset{(6x6)}{[\Phi(t_1 t_o)]} & \multicolumn{2}{c}{[0]} \\ \hline & \underset{(3x3)}{\Psi_1(t_1 t_o)} & [0] \\ \cline{2-3} [0] & [\Psi_3(t_1 t_o)] & [\Psi_4(t_1 t_o)] \end{array}\right] \qquad (3\text{-}55)$$

$$\underset{(12x1)}{\delta y(t)} = \begin{Bmatrix} \{\delta x(t)\} \\ \{\delta W_x\} \\ \{\delta \theta v\} \end{Bmatrix}, \quad \underset{(2x12)}{M} = \left[\begin{array}{c|c|c|c} M_1 & 0 & 0 & M_3 \\ \hline M_4 & 0 & 0 & M_6 \end{array}\right]$$

and $\delta g(t) = \begin{Bmatrix} \delta\phi(t) \\ \delta\theta(t) \end{Bmatrix}$

a least squares solution can be obtained. This would of course involve the computation of the inverse of a 12x12 matrix.

Another technique would consist of employing the minimum variance technique, or Kalman filter, to estimate the state $\{\delta y(t_o)\}$ given set of observations $\{\delta q(t_1)\}$ and an apriori knowledge of the covariance matrix of the $\{\delta y(t_o)\}$. Obviously the state $\{\delta y(t_1)\}$ could also be estimated. Thus after each observation $\{\delta q(t_i)\}$ an updated state $\{\delta y(t_i)\}$ could be obtained. Two possible modes of operation are possible. In the first mode one reference trajectory which is generalized includes satellite position, and velocity as well as vehicle body rates and angles could be employed. In the second mode of operation, the reference trajectory is re-initialized after each observation. This technique is analogous to the Euler Method of celestial mechanics in that the trajectory is rectified, or re-initialized at several different instants of time.

The main advantage of the second technique lies in exploiting one of the advantages of the Kalman Filter, the reduction of the effect of nonlinearities. Since the Kalman Filter gives an optimal estimate of the state vector when the system is under-determined, the length of the time arc over which the linearized system dynamics must be valid can be made small by suitable choice of the observation schedule. Since the trajectory time arcs can be made short, and assuming the process does converge, rectification assures us that the actual trajectory will be close to the true trajectory. This claim cannot be made for the first mode. The requirement for an on-board capability to generate a reference trajectory (as opposed to a stored trajectory) and the extra burden of re-initialization are

disadvantages of the second method. However, to attain reasonable flexibility, the capability to generate reference trajectories via on-board computations is an attractive requirement.

3.4.2 IMC Sensitivities

The desired or required angular rates of the LOS relative to the vehicle are functions of the position and velocity of the satellite, the attitude and attitude rates of the vehicle, and the pitch and roll angles of the LOS. The sensitivity of pitch and roll rates to uncertainties in the above quantities is given in Equations (3-56) and (3-57). The vehicle is assumed to be aligned to the local vertical. x_v is horizontal and down range, y_v is along the local vertical and positive downward, and z_v completes the right-handed system. The quantities V_v and V_θ are the radial and horizontal components of the satellites velocity. Finally, P is the magnitude of the range vector. (δx_v, δy_v, δz_v) and ($\delta \dot{x}_v$, $\delta \dot{y}_v$, $\delta \dot{z}_v$) are the components of $\delta \vec{r}$ and $\delta \dot{\vec{r}}$ along $\vec{i}_v$, $\vec{j}_v$, $\vec{k}_v$. $\delta\theta_{xv}$, $\delta\theta_{yv}$, $\delta\theta_{zv}$ are infintesimal rotations about $\vec{i}_v$, $\vec{j}_v$, $\vec{k}_v$.

The error sensitivities contained in Equations (3-56 and 3-57) are plotted in Figures 3-68 through 3-77.

$$\delta\theta = + \frac{V_r \sin\phi}{p^2 \cos\theta}\begin{bmatrix} -\sin\theta & -\cos\phi\cos\theta & -\sin\phi\cos\theta \end{bmatrix}\begin{Bmatrix} \delta x_v \\ \delta y_v \\ \delta z_v \end{Bmatrix}$$

$$+ \frac{1}{p\cos\theta}\begin{bmatrix} 0 & \sin\phi & -\cos\phi \end{bmatrix}\begin{Bmatrix} \delta \dot{x}_v \\ \delta \dot{y}_v \\ \delta \dot{z}_v \end{Bmatrix}$$

$$+ \frac{1}{\cos\theta}\begin{bmatrix} -\cos\theta & \cos\phi\sin\theta & \sin\phi\sin\theta \end{bmatrix}\begin{Bmatrix} \delta W_{xv} \\ \delta W_{yv} \\ \delta W_{zv} \end{Bmatrix}$$

$$+ \frac{1}{\cos\theta}\left[\left(\frac{V_\theta}{r} \quad \sin\theta \frac{V_v}{p}\right) \quad \left(\sin\theta + \frac{V_o}{r}\cos\theta\sin\phi\right)\right]\begin{Bmatrix} \delta\phi \\ \delta\theta \end{Bmatrix}$$

$$+ \frac{1}{p\cos\theta}\begin{bmatrix} -V_r\cos\phi & -V_o\cos\phi & -V_o\sin\phi \end{bmatrix}\begin{Bmatrix} \delta\theta_{xv} \\ \delta\theta_{yv} \\ \delta\theta_{zv} \end{Bmatrix}$$

(3-56)

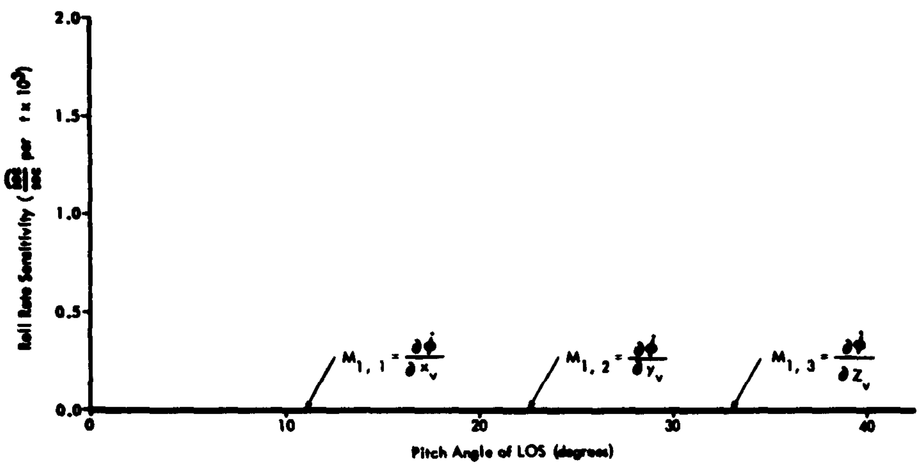

Figure 3-68. Sensitivity of the Roll Rate of the LOS to Uncertainties in the Position of the Satellite (Landmark 60 n mi Out of Orbital Plane)

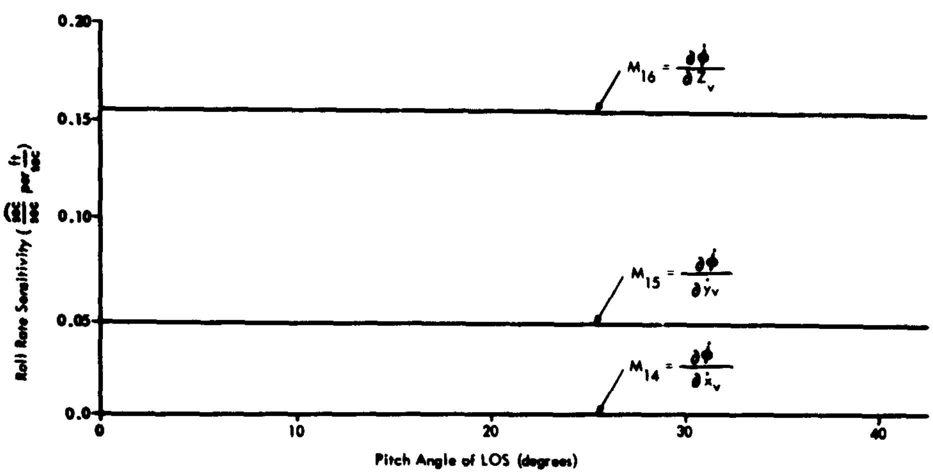

Figure 3-69. Sensitivity of the Roll Rate of the LOS to Uncertainties in the Velocity of the Satellite (Landmark 60 n mi Out of Orbital Plane)

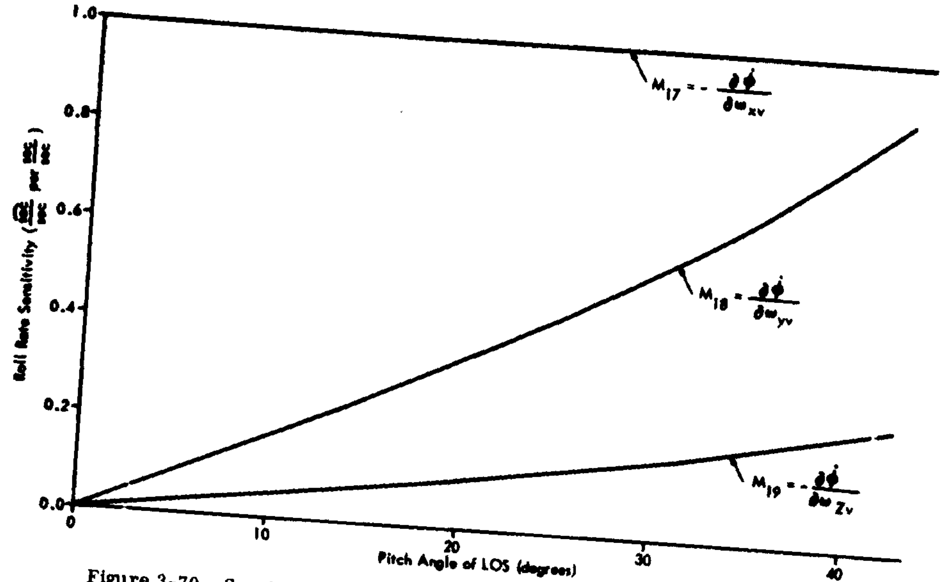

Figure 3-70. Sensitivity of the Roll Rate of the Line of Sight to Uncertainties in the Vehicle Angular Velocity

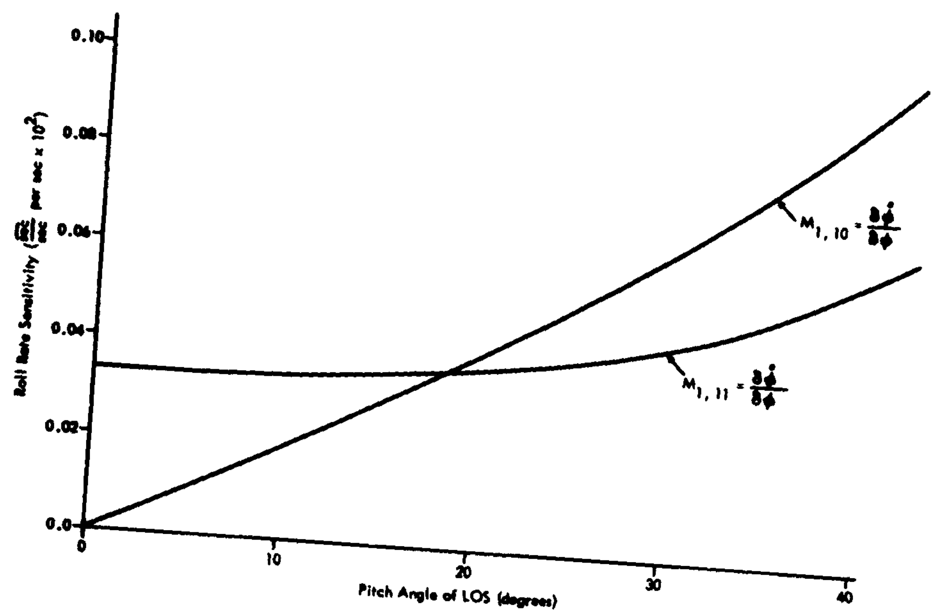

Figure 3-71. Sensitivity of the Roll Rate of the LOS to Uncertainties in the Angular Orientation of the Line of Sight Relative to the Vehicle (Landmark 60 n mi Out of the Orbital Plane)

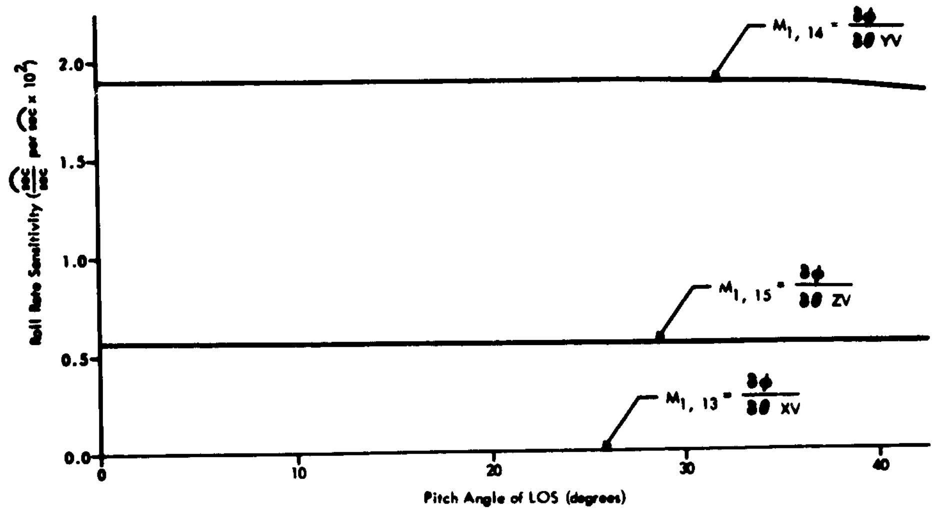

Figure 3-72. Sensitivity of the Roll Rate of the LOS to Uncertainties in the Vehicle Attitude (Landmark 60 n mi Out of the Orbital Plane)

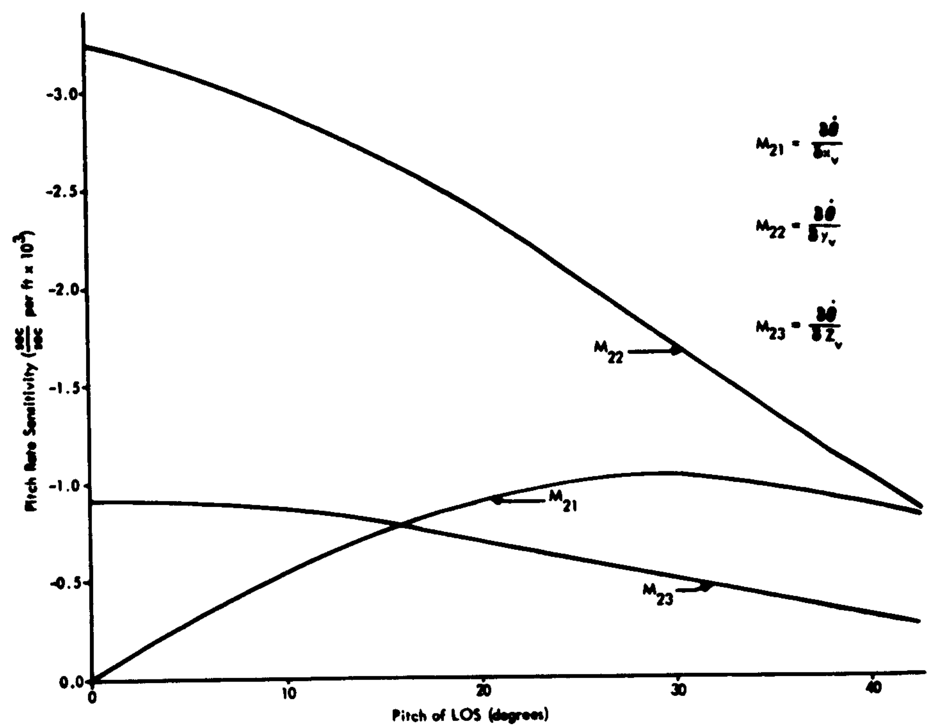

Figure 3-73. Sensitivity of the Pitch Rate of the Line of Sight to Satellite Position Uncertainties (Landmark 60 n mi Out of Orbital Plane)

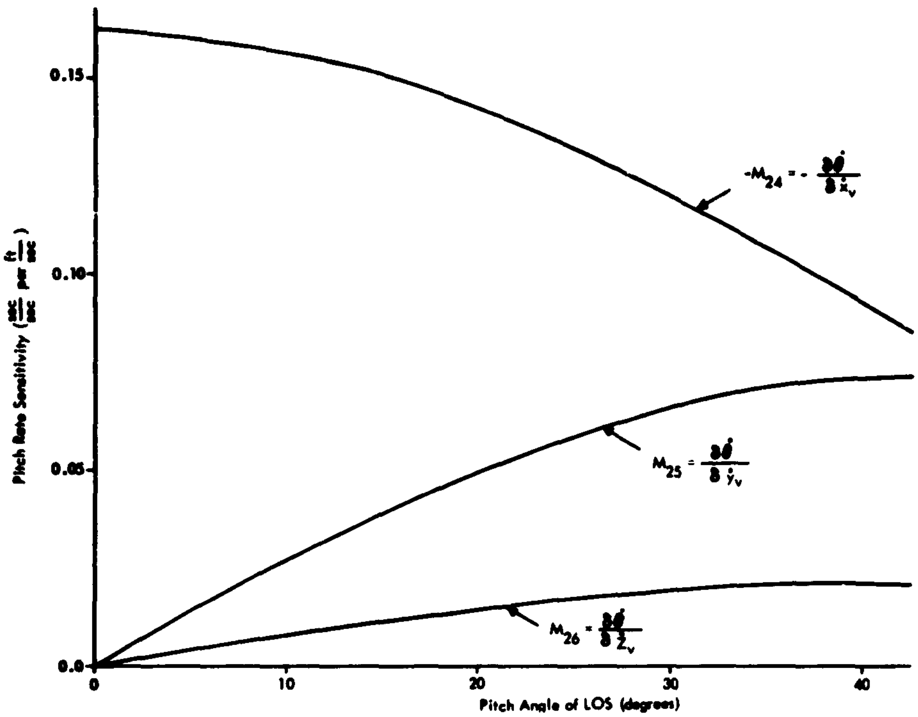

Figure 3-74. Sensitivity of the Pitch Rate of the LOS to Uncertainties in the Velocity of the Satellite (Landmark 60 n mi Out of Orbital Plane)

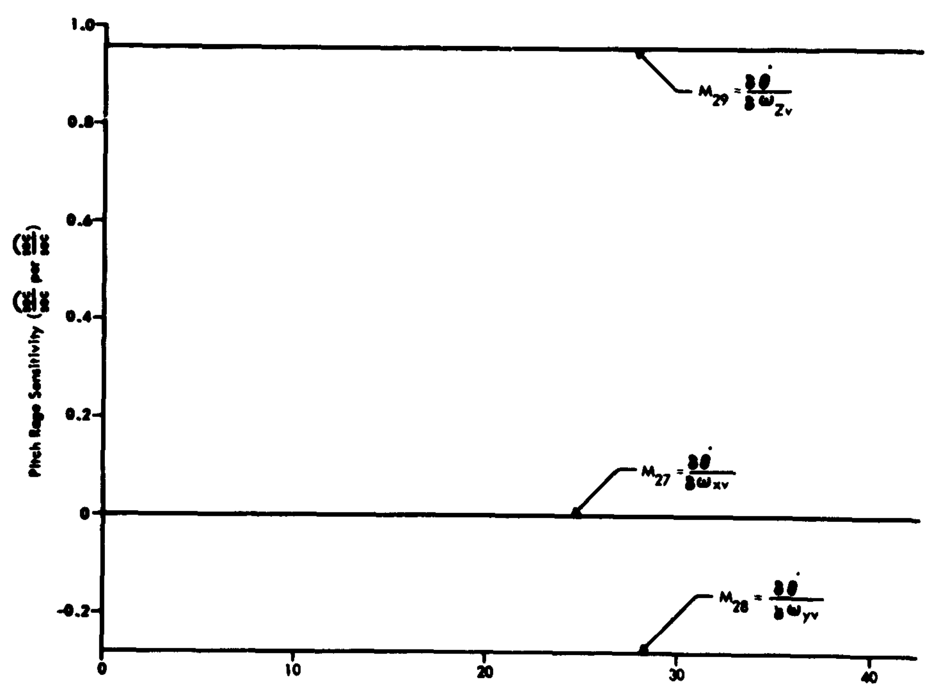

Figure 3-75. Sensitivity of the Pitch Rate of the LOS to Uncertainties in the Vehicle Angular Velocity (Landmark 60 n mi Out of Orbital Plane)

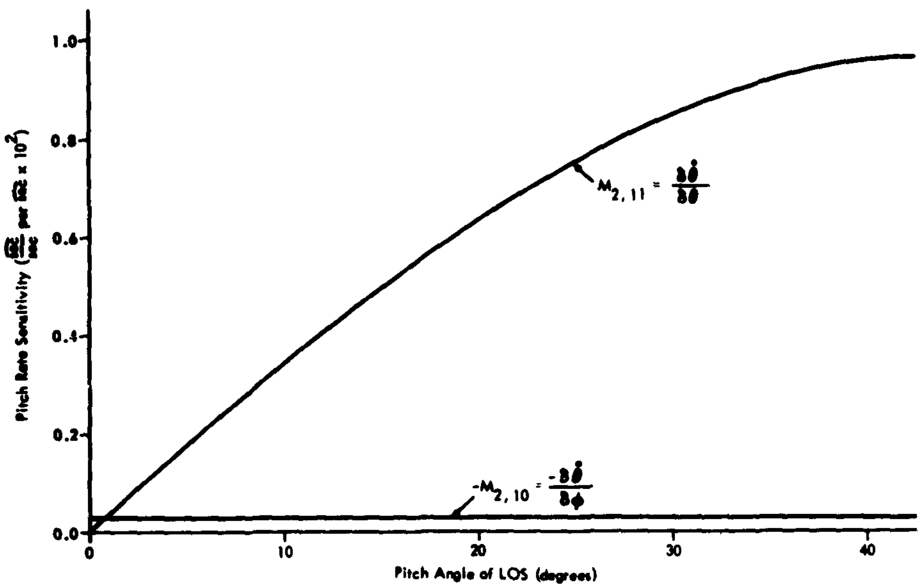

Figure 3-76. Sensitivity of the Pitch Rate of the LOS to Uncertainties in the Angular Orientation of the Line of Sight Relative to the Vehicle (Landmark 60 n mi Out of Orbital Plane)

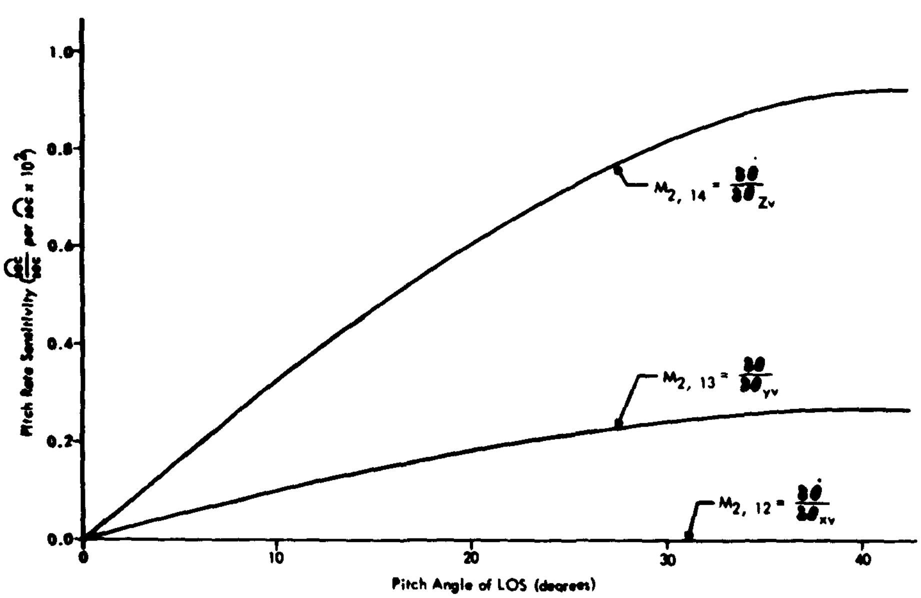

Figure 3-77. Sensitivity of the Pitch Rate of the Line of Sight to Uncertainties in the Attitude of the Vehicle (Landmark 60 n mi Out of the Orbital Plane)

$$\delta\theta = -\frac{V_o\cos\theta + V_r\cos\phi\sin\theta}{p^2}\begin{bmatrix}\sin\theta & \cos\phi\cos\theta & \sin\phi\cos\theta\end{bmatrix}\begin{Bmatrix}\delta x_v\\ \delta y_v\\ \delta z_v\end{Bmatrix}$$

$$+\ \frac{1}{p}\begin{bmatrix}-\cos\theta & \cos\phi\ \sin\theta & \sin\phi\ \sin\theta\end{bmatrix}\begin{Bmatrix}\delta\dot{x}_v\\ \delta\dot{y}_v\\ \delta\dot{z}_v\end{Bmatrix}$$

$$+\ \begin{bmatrix}0 & -\sin\phi & \cos\phi\end{bmatrix}\begin{Bmatrix}\delta W_{xv}\\ \delta W_{yv}\\ \delta W_{zv}\end{Bmatrix} \tag{3-57}$$

$$+\ \left(\frac{V_r\sin\phi\ \sin\theta}{p}\quad \frac{V\theta\ \sin\phi}{r}\right)\left(-\frac{V\theta}{p}\ \sin\theta\ -\frac{V_r\cos\theta}{p}\ \cos\phi\right)\begin{Bmatrix}\delta\phi\\ \delta\theta\end{Bmatrix}$$

$$+\ \frac{1}{p}\left[V_r\sin\phi\ \sin\theta \quad V_o\sin\phi\ \sin\theta\,(V_r\cos\theta\left(-V \quad \cos\phi\sin\theta\right)\right]\begin{Bmatrix}\delta\theta_{xv}\\ \delta\theta_{yv}\\ \delta\theta_{zv}\end{Bmatrix} \tag{3.4-38}$$

The sensitivities are plotted for a typical example in Figures 3-68 through 3-77. The target is 60 n mi to the left of the orbital plane. The orbit of the satellite is circular at 200 n mi altitude. The three variables p, θ, ϕ are not all independent. The pitch angle θ was chosen as the independent parameter for the graphs in Figures 3-68 through 3-77 instead of time. In other words, p and ϕ were considered to be the functions of proper functions of θ to track the specified target.

For the data presented in the graphs, the roll angle was practically constant, varying from 16.4 to 16.7 degrees. The slant range p varied from 292 to 209 n mi at zero pitch. For the chosen circular orbit, the nominal values of the pitch and roll rates are

$$\theta = \frac{-V_\theta}{p}\cos\theta + \frac{V_\theta}{r}\cos\phi$$

$$\dot{\phi} = \frac{V_\theta}{r}\,\frac{\sin\phi\sin\theta}{\cos\theta}$$

Since $p/r \sim 1/15$, the desired angular rate is approximately given by $\dot{\theta}$. Thus

$$\dot{\theta} \approx \frac{V_\theta}{p}\cos\theta$$

The IMC may be approximately estimated from $\delta\dot{\theta}/\dot{\theta}$ and $\delta\dot{\phi}/\dot{\theta}$.

3.4.3 Selection of State Variables

The number of state variables that need to be employed in an IMC filter depends on the size of the IMC sensitivities as well as on the particular choice of possible states. For example, if by suitable choice some of the states are uncoupled in the state transition matrix and, observation matrix, and, in addition, these states have a small effect on the IMC, then these states could be eliminated. Specifically, the out-of-plane distance and velocity may be uncoupled from in-plane components in variational equations by choosing a coordinate system aligned to the orbital plane. This causes the uncoupling of the in-and out-of-plane components in the state transition matrix. Additionally the out-of-plane velocity does not effect observations and the out-of-plane position is weakly coupled in the observation matrix for pitch angles. Furthermore, the out-of-plane components of position and velocity have small effect on pitch rate. Thus, the out-of-plane components of vehicle position and velocity might safely be neglected for pitch rate.

Bias errors such as target location and boresight errors can be added to the number of states employed. If these are neglected, "spurious corrections" are made to the ephemeris update process. It is believed that these spurious corrections will not be detrimental when one target is to be tracked, but will cause sudden transient errors when the LOS of the PTS is transferred from one target to another. Additionally, the IMC error will gradually increase with lapsed time after the manual control stopped.

Table 3 - 12 shows the relative importance of the state variables, assuming a ground navigation update of 500 feet and 2 fps along all axes, which is propagated forward 45 degrees in the orbit to the target area to be tracked. Errors in X and Z only contribute initial pointing errors, which are eliminated by the astronaut upon target acquisition. This makes sense since δX and δZ are mere translations with respect to the target that cause initial pointing errors in pitch ($\delta \theta$) and roll ($\delta \phi$), which the astronaut then reduces to about 10 arc seconds. The velocity errors of 85 fps are obtained as projections of the orbital velocity along the body axes which can be in error with respect to the velocity vector by about 0.2 degree in all axes.

A list of state variables that are tentatively recommended for inclusion in an IMC filtering concept is presented in Table 3-13.

The yaw rate of the vehicle is only important for pitch rate when dealing with out-of-plane targets. Since yaw rate also affects roll rate, it would be a likely candidate for elimination as a state variable by employing a

Table 3-12
RELATIVE IMPORTANCE OF IMC SENSITIVITY PARAMETERS

(Landmark 60 n mi Out of Orbital Plane)

Parameter	1σ Error	Roll Rate Error $\widehat{sec}$./sec.	Pitch Rate Error $\widehat{sec}$./sec.	Remarks
X	1350 ft	0	1.4*	Errors propagated
Y	1800 ft	0	5.8	45^{o} geocentric downrange
Z	1200 ft	0	1	$\delta X_o = \delta Y_o = \delta Z_o = 500$ ft
X	85 fps	0	12.8	Initial velocity error = 85 fps
Y	85 fps	4.2	6.0*	$\delta X = \delta Y_o = \delta Z_o = 85$ fps
Z	85 fps	12.8	1.7*	25000 x (attitude error) 0.2^{o}
θ	± 10 $\widehat{sec}$	0.004	0.09*	Includes errors attributed to man, hand control and servos
ϕ	± 10 $\widehat{sec}$	0.006	0.01	
ω_x	± 36 $\widehat{sec}$ /sec	36	0	
ω_y	± 36 $\widehat{sec}$ /sec	21.6*	10.8	0.01^{o}/sec after attitude control system is turned off
ω_z	± 36 $\widehat{sec}$ /sec	5.76*	35	
θ_x	720 $\widehat{sec}$	0	0	
θ_y	720 $\widehat{sec}$	13.0	1.7*	± 0.2^{o} horizon sensors and orbital alignment assumed
θ_z	720 $\widehat{sec}$	3.6	5.6*	

Table 3-13
RECOMMENDED LIST OF STATE VARIABLES
FOR INCLUSION IN IMC FILTER

Roll Rate ($\dot{\phi}$)		Pitch Rate ($\dot{\theta}$)	
Horizontal cross velocity	$\dot{Z}$	Altitude	Y
Vehicle roll rate	ω_x	Horizontal in-plane velocity	$\dot{X}$
Vehicle yaw rate	ω_y	Vehicle yaw rate	ω_y
Vehicle yaw attitude	θ_y	Vehicle pitch rate	ω_z
		Vehicle pitch attitude	θ_z

good yaw rate gyro (better than 5 degrees random drift). Similar trade-off could be employed for the remaining state variables to keep the computational load within reason.

For a comprehensive evaluation of IVSS - astronaut performance that can be conducted on the ground, there is little reason for not including all state variables that contribute more than 2.5 arc seconds/second (0.05 percent of nadir angular rate). This would mean (from Table 3-12) pitch rate and seven roll rate state variables.

Preliminary instrumentations of the above state variables are shown in Section 4.2 for both the analog and digital instrumentations.

The states contained in Table 3-12 are not necessarily optimum from an instrumentation viewpoint, and, it may be more expedient computation-wise to employ states corresponding to either spherical or cylindrical coordinates and their time rates of change. Another possibility is to employ a coordinate system that is aligned to the LOS, i.e., one that is rotated from the vehicle body axes through the pitch and roll angles of the LOS.

3.4.4 Orbit Parameter Update Studies

A digital simulation of the differential correction technique employing a Kalman filter was performed for a candidate IVSS instrumentation scheme referred to in Section 4.0 as the "Extended Capability" mode. The state variables employed for the study were necessarily the six orbital parameters using pitch and roll of the LOS as the observables. The contractual study period did not allow for additional state variables, such as vehicle attitude and attitude rates along with bias errors, to be incorporated in the simulations.

The reason for this was the existence at IBM of an operational Kalman Filter which was specifically oriented towards orbit ephemeris updating. Studies are being conducted to generalize the filter for more variables. The program employs a point mass model of the satellite, a spherical non-rotating earth, and inverse square law potential field.

The construction of the filtering program was such that it was most convenient to assign initial apriori covariances of position and velocity deviations at integral multiples of 180 degrees before observations were taken. In the simulation runs presented in Figures 3-78 and 3-79, the initial covariance matrix of position and velocity deviations was taken to be a diagonal matrix, the standard deviation of each rectangular coordinate of position being 300 feet, and the standard deviation of each rectangular coordinate of velocity being 2 fps. This is consistent with the quote accuracy of SPADATS data for determining the ephemeris of a friendly

satellite. In the simulation, 180 degrees was chosen as the interval of propagation between the initial covariance matrix and the time of first observation on the ground targets. In all simulation runs, the location of the ground target was chosen to be on the ground track of the true satellite orbit. Furthermore, the noise in distinct observations was taken to be uncorrelated. This assumption is consistent with human factors' studies of man's tracking capability made on the Earth Sighting Simulator.

Figures 3-78 and 3-79 present graphs of IMC as a function of the standard deviation of measurement errors, the time between observations, and the total number of observations. Figure 3-80 is a plot of navigation errors versus time from first fix. The σ of 25 arc seconds was chosen because it appears from observation of Figures 3-78 and 3-79 that this is an acceptable error criteria to use for both IMC and autonomous navigation.

Figure 3-78 shows plots of IMC versus time for observation errors of 90, 60, and 40 arc seconds, and observation frequencies of 14 observations 3 seconds apart, and nine observations 5 seconds apart.

In the 7090 program, the observation errors were chosen as random angles from a normal population of mean zero and standard deviations as noted on the graphs. However, for any group of 5 or 14 observations, the sample mean will not be zero nor will the sample standard deviation be equal to the population sigmas specified in the curves. Therefore, it is quite reasonable to expect our intuition, as to what should happen to IMC as sigmas go up and number of observations go down fails some of the time.

The trend, however, is as would be expected in Figure 3-78.

In Figure 3-79, the 15 arc second curves show that nine observations 5 seconds apart are better than 14 observations 3 seconds apart. This is attributed to larger errors during the latter observations produced by the random noise particular to the samples chosen.

To alleviate this situation, it would be advisable in the next phase to plot the standard deviation of percent IMC instead of the actual IMC or to use Monte Carlo simulation. These figures indicate that it appears feasible that this filtering technique will reduce IMC down to 0.05 percent for reasonable measurement errors and fix frequencies for periods up to 100 seconds. This has the advantage of easing up on the focal length requirement spelled out in Section 3.2.1. This is discussed more thouroughly in Section 4.2

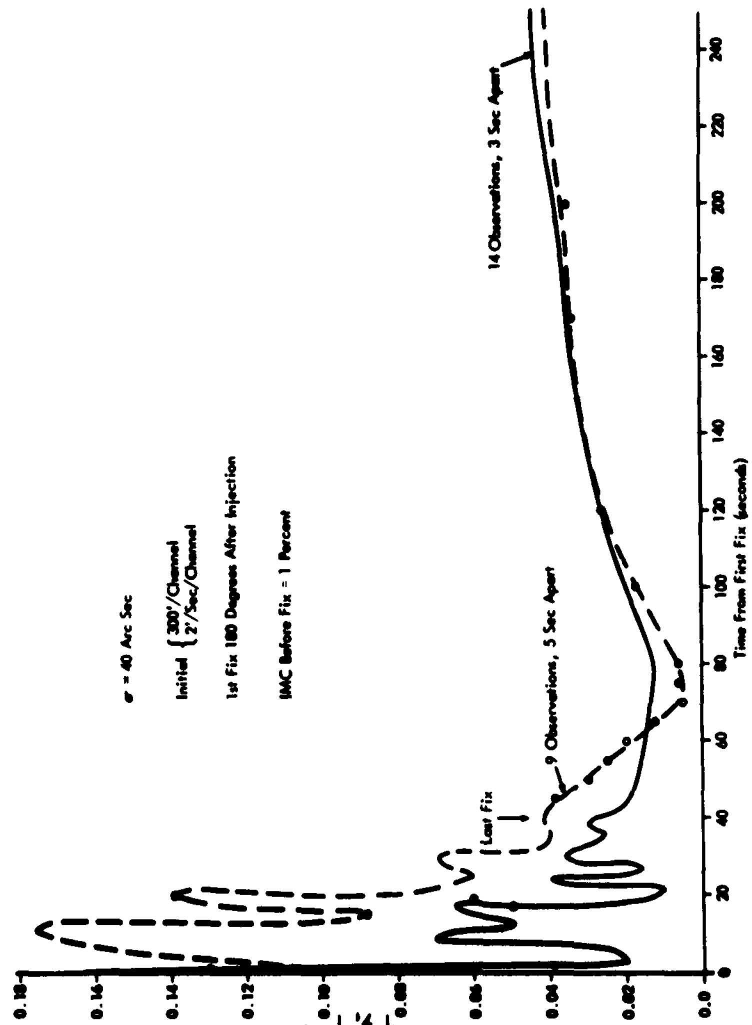

Figure 3-78. IMC (percent) vs Time for Observation Errors of 90, 60, and 40 Arc Seconds (Sheet 1 of 3)

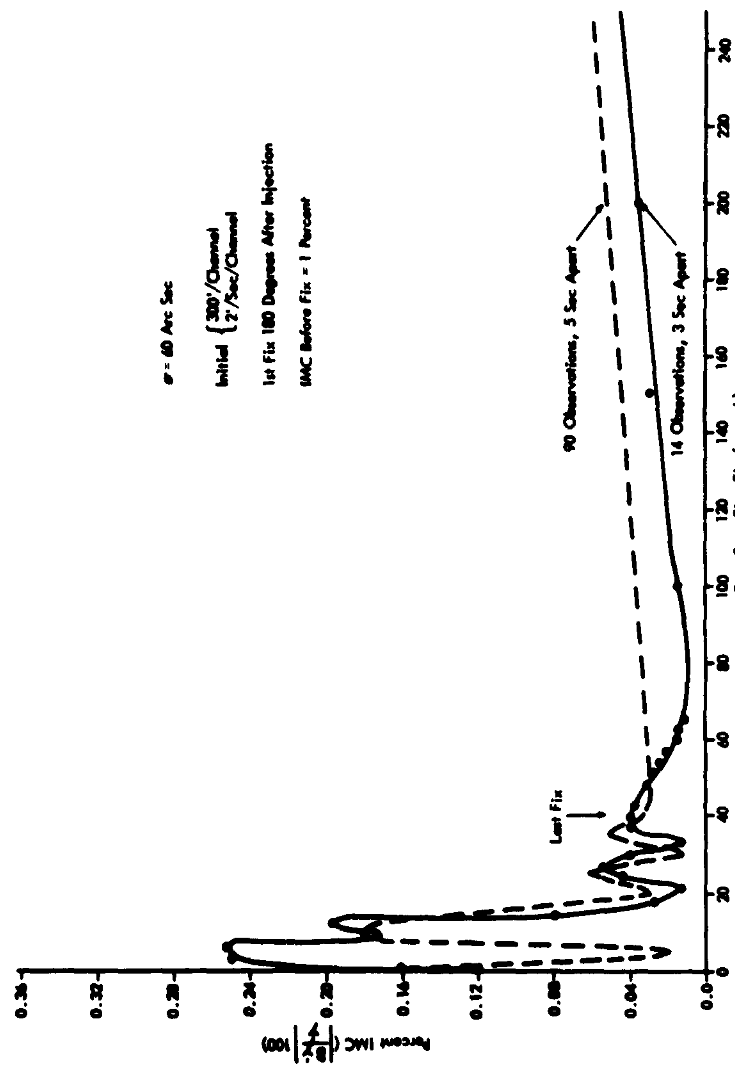

Figure 3-78. IMC (percent) vs Time for Observation Errors of 90, 60, and 40 Arc Seconds (Sheet 2 of 3)

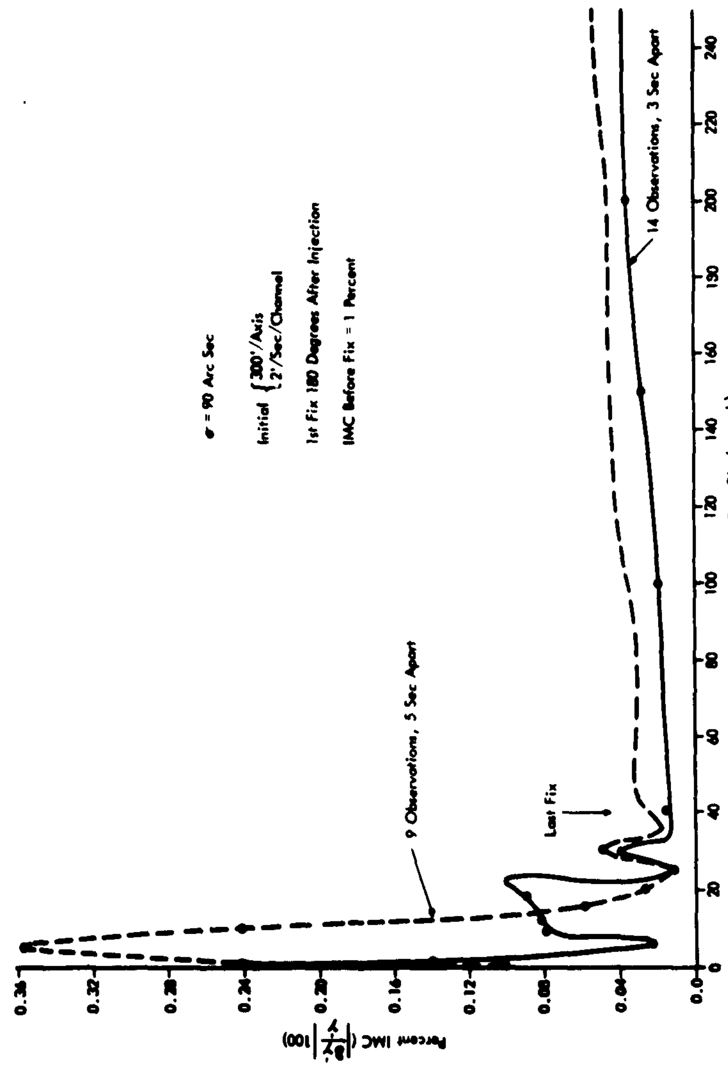

Figure 3-78. IMC (percent) vs Time for Observation Errors of 90, 60, and 40 Arc Seconds (Sheet 3 of 3)

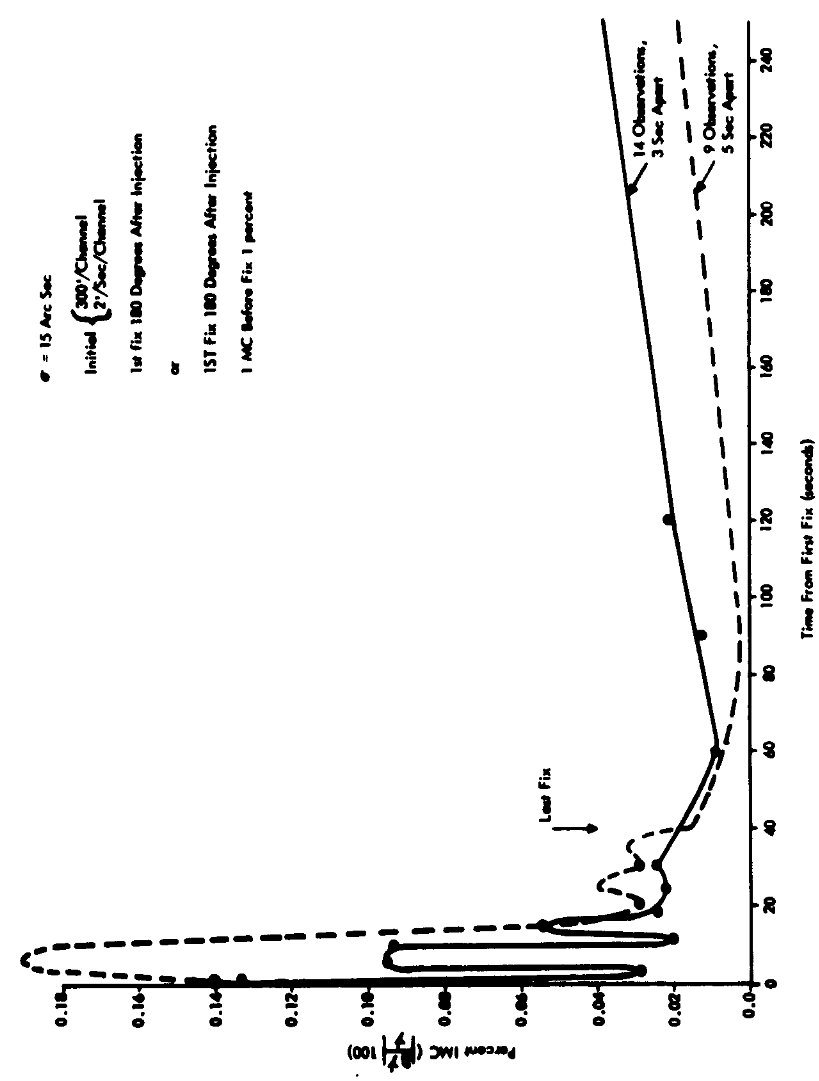

Figure 3-79. IMC (percent) vs Time for Observation Errors of 15 and 25 Arc Seconds (Sheet 1 of 3)

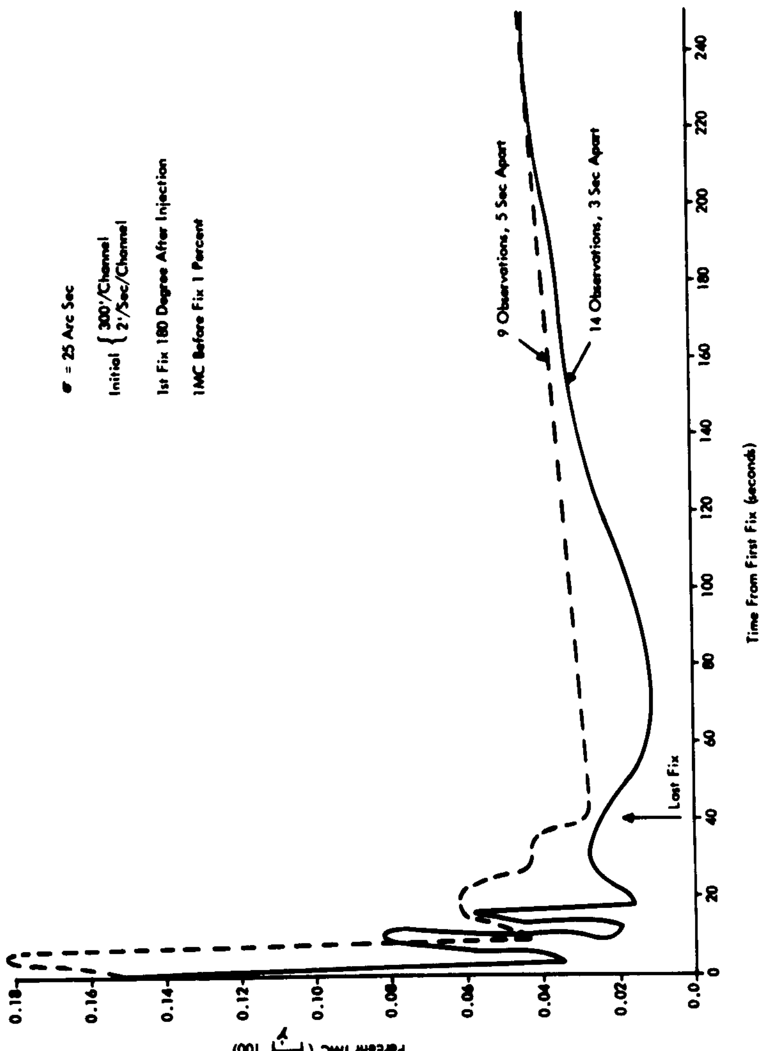

Figure 3-79. IMC (percent) vs Time for Observation Errors of 15 and 25 Arc Seconds (Sheet 2 of 3)

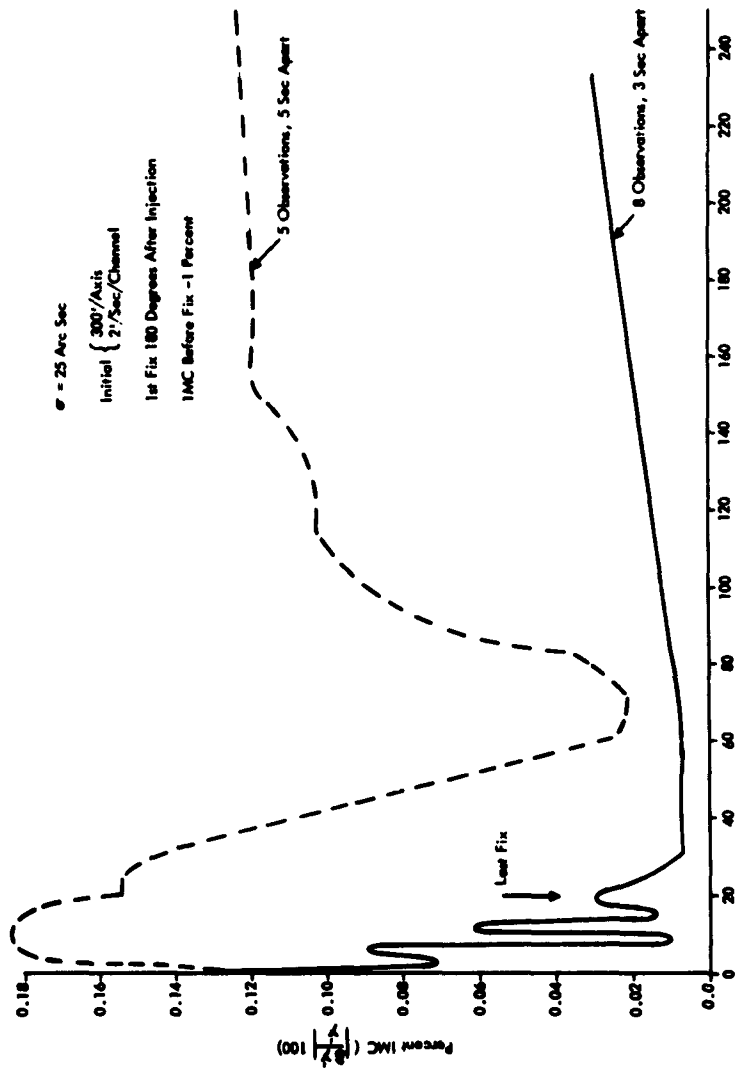

Figure 3-79. IMC (percent) vs Time for Observation Errors of 15 and 25 Arc Seconds (Sheet 3 of 3)

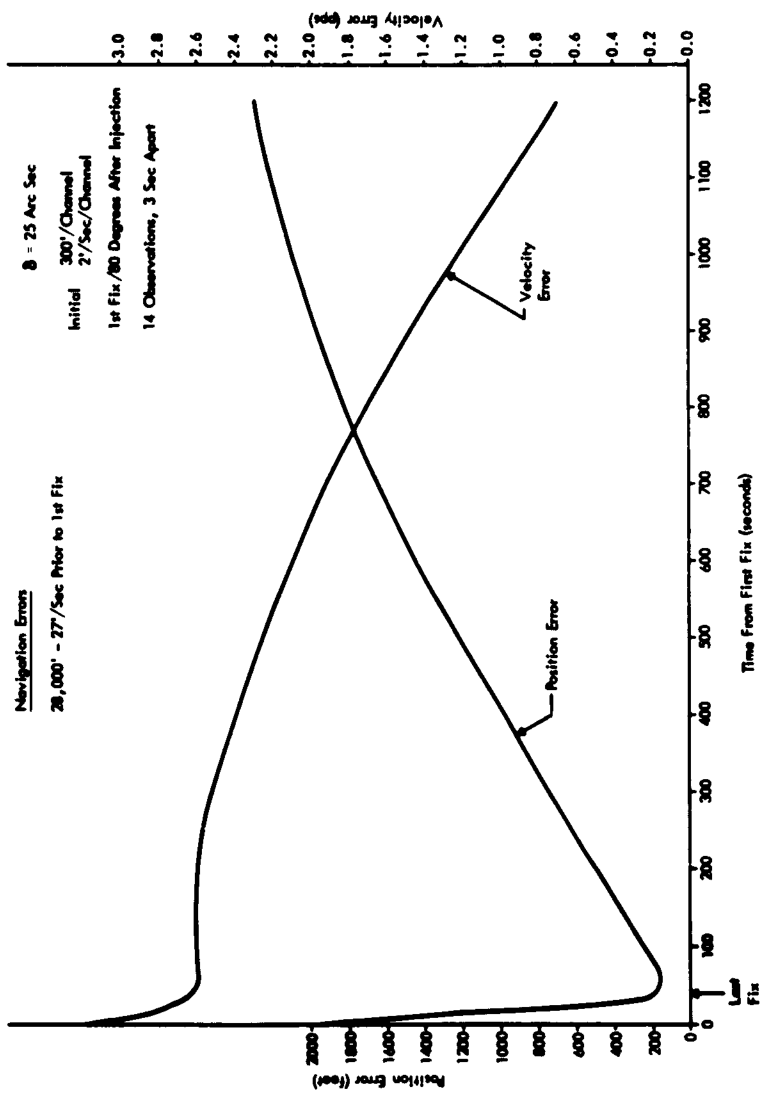

Figure 3-80. Navigation Errors vs Time

3.5 Automatic Scanning Studies

This subsection presents the results of the studies associated with two automatic scan patterns that appear promising for acquiring ground targets. These are the boustrophedon and the spiral scans. The boustrophedon (Figure 3-81) scan is used to sweep out an area at essentially a fixed obliquity angle ahead of the vehicle. The spiral scan is used primarily for targets whose location is fairly well known.

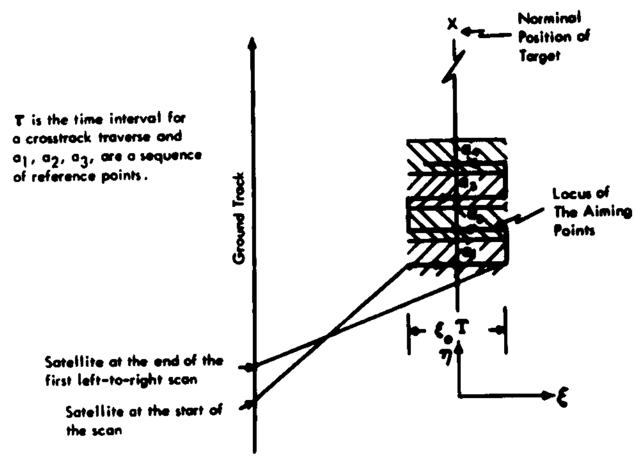

Figure 3-81. Schematic of the Boustrophedon or Raster Scan

The scan equations, were developed to give the system the capability to acquire any target with a minimum of prestored constants; i.e., target-trajectory-dependent constants. Additionally, a degree of flexibility was incorporated to allow for several different operational situations (described in Volume IV):

(a) Boustrophedon scan about orbit plane at a fixed nominal obliquity angle (30 to 45 degrees).

(b) Boustrophedon scan about an out-of-plane locus determined by out-of-plane distance of:

- Coordinates of expected target location.
- Manual positioning of PTS - LOS when automatic boustrophedon scan is initiated.

(c) Spiral scan about nominal aimpoint determined by:
- Stored coordinates of expected target location.
- Position of PTS - LOS when automatic spiral scan is initiated.

Further effort could be directed toward modifying these equations so that the over-all probability of detection will be maximized for the operational situation of interest. Additionally, changes made to increase the probability of detection (such as increasing the amount of overlap at the expense of swath width) wouldhave to be weighted against increased onboard computational requirements and/or decreased flexibility.

3.5.1 The Boustrophedon Scan

The Boustrophedon or "Carpet Sweep" Scan was designed so the scan pattern could be continued indefinitely. Thus, the time from the start of a left-to-right scan to the start of the next right-to-left scan (γ) is given by

$$\tau = \frac{2a}{R\dot{\theta}_o}$$

where 2a is the major axis of the ellipse when the scan pattern crosses the ground track, $\dot{\theta}_o$ is the orbital angular velocity of the satellite, and R is the radius of the earth. For simplicity, the PTS aiming point was chosen to have a constant linear velocity $\dot{\zeta}$ relative to the aiming point on the surface of the earth. The magnitude of the linear velocity was computed from the approximate equation

$$\dot{\zeta} = \omega_a \ (r - R)/M$$

where ω_a is the allowable apparent angular rate of the LOS in the eyepiece (ω_a = 8 deg./sec), where M is the magnification and r is orbital radius. Figure 3-82 shows the progression of the aiming points in a left-to-right scan, where the field of view (the intersection of the conical beam and the horizontal plane) is an ellipse of moderate eccentricity. It can be seen from the figure that the "in-track" width of the field of view is practically constant while the major axis of the ellipse varies by approximately 20 percent. Thus, in the succeeding right-to-left scan there is no area "missed" and the overlap is negligible, so, in this sense, an efficient scan pattern is achieved.

Let the width of the scan pattern be defined as the distance the aiming point moves in a left-to-right scan. This is a fairly accurate definition for high obliquity angles, and is conservative when the scan occurs with approximately zero pitch. For this definition, the width of the carpet sweep is given by:

$$\text{Width} = \frac{\omega_a (r - R)\, 2a}{R\,\dot{\theta}_o\, M}$$

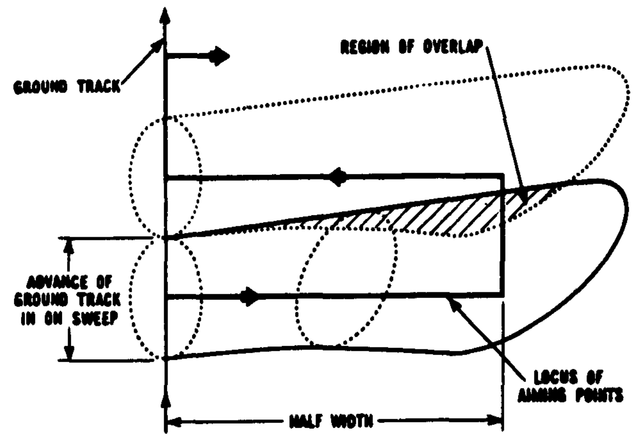

Figure 3-82. Progression of Aiming Points in a Left-to-Right Scan

Thus the width of the scan pattern is a linear function of the major axis (2a). Obviously, the major axis is a function of the obliquity angle and the half angle of the conical beam (which is inversely proportional to the magnification). Thus the width of the scan increases with increasing obliquity angle and decreases with increasing magnification. The curves in Figure 3-83 illustrate these dependencies.

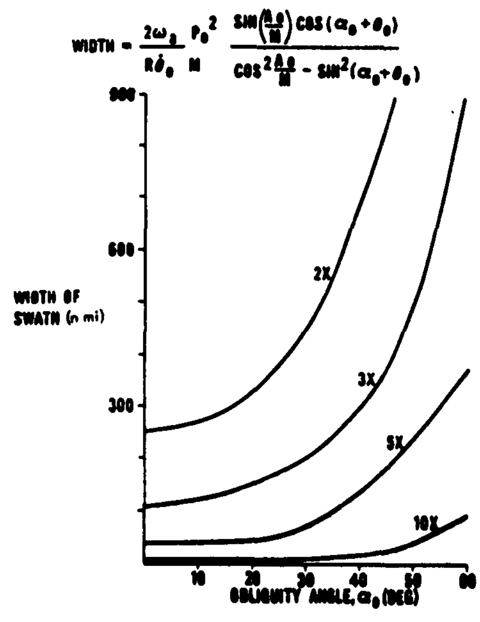

Figure 3-83. Variation of Swath Width with Magnification and Obliquity Angle
(Maximum Angle Rate of Line of Sight = 8 Deg/Sec at 1X)

3.5.2 The Spiral Scan

The spiral scan shown in Figures 3-84 through 3-86 is initiated when the geocentric downrange angle to the reference point (center of the spiral scan) is 3.288 degrees down range and 1 degree cross range. The figures show the focus of the aiming points for somewhat more than two and one half circuits around the spiral, each circuit being shown separately. At the high obliquity angles, the field of view at any instant is highly elliptical, as is the case in traversing the spiral from δ = 90 degrees to δ = 360 degrees (Figure 3-84). In traversing the second loop of the spiral (δ = 360 degrees to δ = 720 degrees) (Figure 3-85), a small area near the reference point was not observed (this was covered during the first loop). The third loop (Figure 3-86) shows an increased central area that does not come within the field of view of the scan pattern. Additionally, the size of the field of view near δ = 940 degrees has been severely attenuated and in fact is nearly circular.

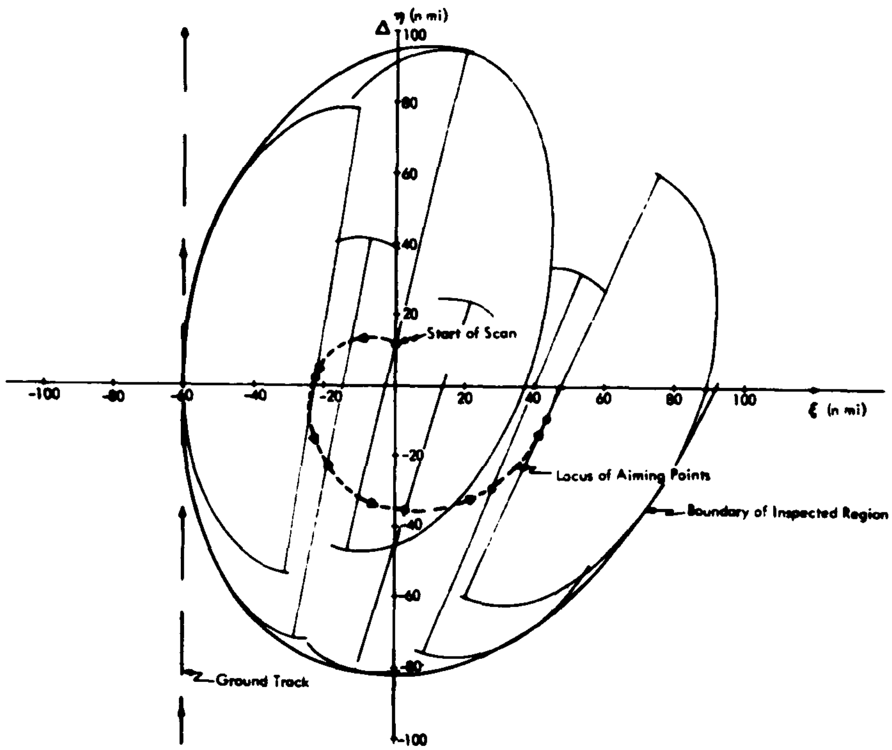

Figure 3-84. Geometry of a Spiral Scan-Area Inspected During First Loop of Spiral

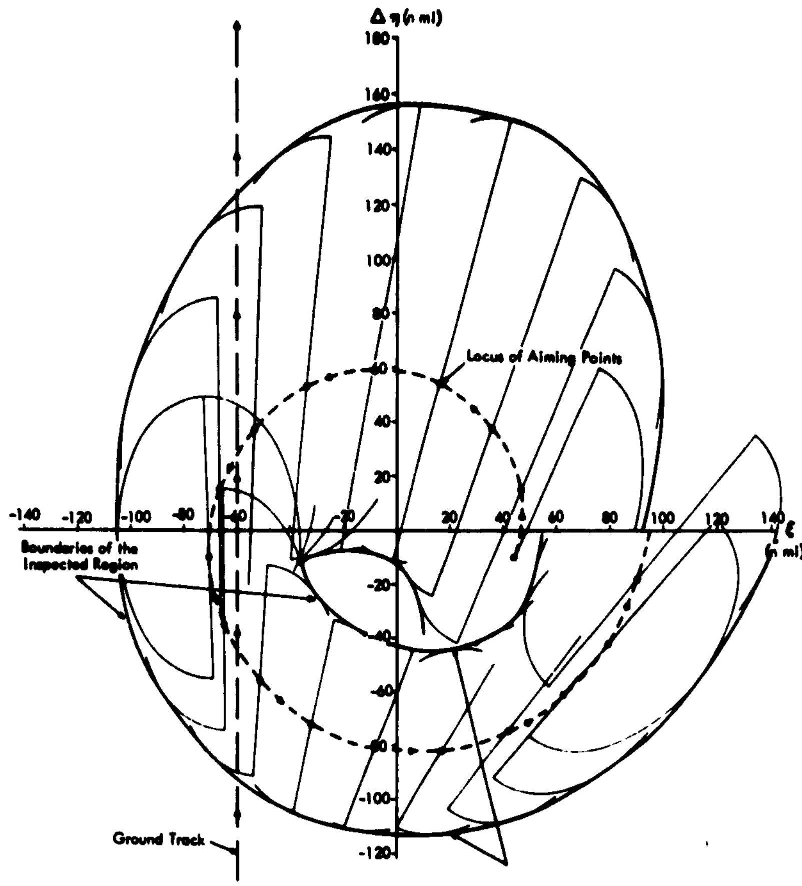

Figure 3-85. Geometry of a Spiral Scan-Area Inspected During Second Loop of Spiral

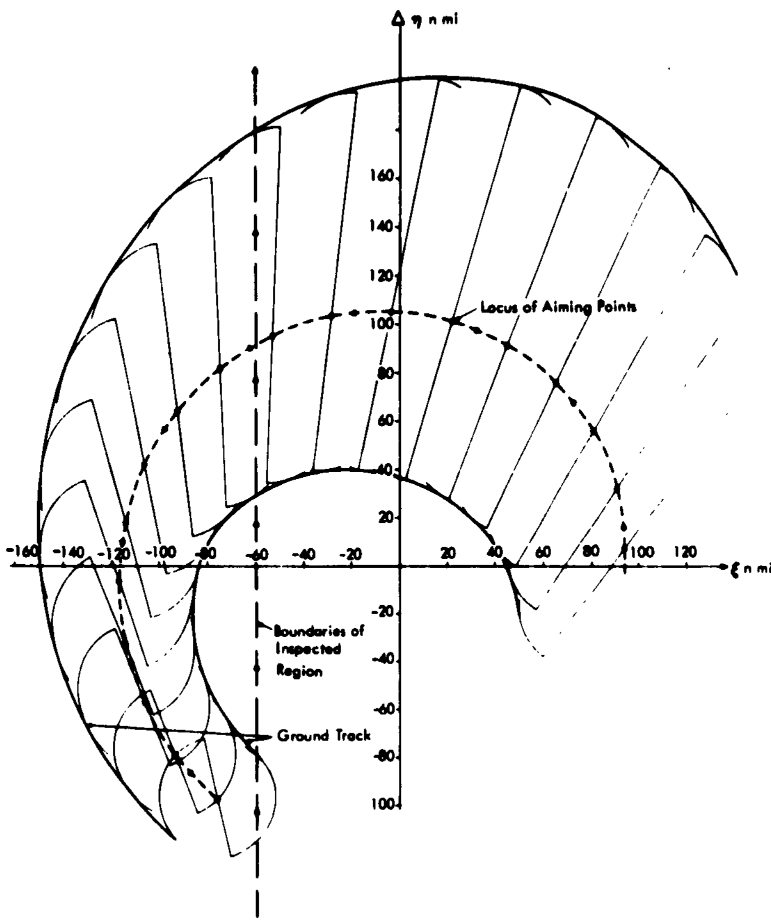

Figure 3-86. Geometry of a Spiral Scan-Area Inspected During Third Loop of Spiral

The superposition of these three loops shows a great amount of overlap, which is desirable if a significant increase in the probability of detection is to be realized by having the target appear within the field of view more than once. The penalty for the overlap is of course, a decrease in the total area searched during the spiral scan.

The configuration shown in Figures 3-84 through 3-86 is rather extreme in that high obliquity angles are encountered. If the spiral scan were commenced at a later time (i.e., smaller downrange angle to the center of the spiral scan), the amount of overlap would be drastically reduced. Indeed, the total area of search would also be reduced.

Two methods of eliminating the overlap consist of (1) appropriately deforming the Archimedian spiral; or (2) employing a "zoom" lens. The latter technique would require increased magnification as the angle of incidence was increased. This would decrease the amount of overlap and at the same time counteract the decrease in the apparent size caused by the increased obliquity. Additionally, since the detection process is adversely affected by high angles of incidence, the zoom capability would allow an increase in the apparent size of the target as would be the case if this magnification were proportional to the major axis of the ellipse; i.e.,

$$\text{magnification} \propto 2a$$

instead of

$$\text{magnification} \propto \frac{1}{\cos \beta}$$

which would make the apparent size of the target independent of the angle of incidence.

If the probability density function for the target to be at a given point within a prescribed region is constant, a finite Boustrophedon scan is to be preferred. (A finite Boustrophedon scan is one that has a finite dimension parallel to the ground track.) If the probability function is normally distributed, the spiral scan might be preferred. Additionally, the choice will depend on the knowledge of the dependence of the probability of detection on magnification, obliquity, and angular rate of the LOS.

3.6 Vehicle Interface Studies

The following four significant vehicle interface studies were performed during this phase of the IVSS study:

*(1) PTS gimballing studies to determine:
   (a) gimbal configuration
   (b) gimbal/vehicle installation
   (c) maximum gimbal rates and accelerations for ground and space targets.

*(2) Attitude Control studies to determine:
   (a) fuel required to roll the vehicle instead of utilizing the roll gimbal of the PTS when tracking a target,
   (b) vehicle disturbances due to scanning mirror rates while searching for a target,
   (c) vehicle attitude displacement due to gravity gradient torques when the attitude control system is turned off, and
   (d) vehicle orientation in orbit and estimated fuel required to maintain attitude. (Station-keeping would be a separate MOL vehicle study.)

(3) IVSS attitude reference sensors and their installation to minimize PTS alignment problems.

(4) Feasibility of frequent ground updates which would preclude fix taking in orbit.

3.6.1 Gimbal Study Results

The results of the gimbal study show that (1) a two-gimbal system is required to enable an astronaut to make vernier corrections in two axes, and (2) the gimbal arrangement for the PTS should be such that the probability of a target lying near the outer gimbal axis is small because gimbal rates and accelerations approach infinity when the target is near this axis.

The reasons for conclusion 2 can be demonstrated by referring to Figure 3-87, where "a" is the distance of the target from the ground track, "b" is the altitude of the vehicle orbit, and $\vec{\rho}$ is the LOS vector.

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* The principle reference for these studies is "An Investigation of Certain Attitude Control System Considerations for Pointing a Telescope from MOL", which is in the Data Source Handbook.

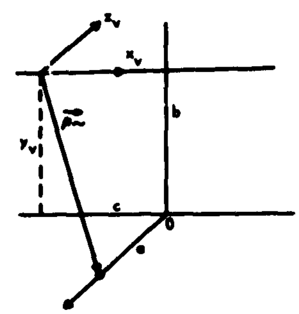


Figure 3-87. Geometry For Azimuth/Elevation Coordinate System

For a flat earth approximation in the vicinity of the target and a vehicle velocity, V, in the direction of vehicle x-axis, the LOS vector can be expressed in vehicle coordinates as

$$\vec{\rho}(t) = (c - Vt)\,\vec{i} + b\,\vec{j} - a\ \ k\,. \tag{3-58}$$

The azimuth gimbal angle (about the x axis) is given by

$$\theta = \tan^{-1}\left(\frac{-\rho z}{\rho x}\right) = \tan^{-1}\left(\frac{-\ a}{Vt - c}\right), \tag{3-59}$$

from which

$$\dot{\theta} = \frac{a\,V}{(Vt - c)^2 + a^2}\,, \tag{3-60}$$

and

$$\ddot{\theta} = \frac{-2\,a\,V^2\,(Vt - c)}{\left[(Vt\ \theta c)^2 + a^2\right]^2}\,. \tag{3-61}$$

Maximum gimbal rate occurs when $t = \frac{c}{V}$ (i.e., when the vehicle is over point 0) and its value is $\dot{\theta}_{max} = V/a$, which shows that as "a" approaches zero, $\dot{\theta}$ approaches infinity.

It can be shown that $\ddot{\theta}$ extremes occur when

$$t = \frac{c \pm a/\sqrt{3}}{V} \tag{3-62}$$

Substituting Equation (3-62) into Equation (3-61), $\ddot{\theta}_{max}$ is found to be

$$\ddot{\theta}_{max} = \frac{3\sqrt{3}}{8}\ \frac{V^2}{a^2} \tag{3-63}$$

Equation (3-63) shows the same singularity when the distance of the target from vehicle ground track approaches zero.

The pitch and roll gimballing combination (see Figure 3-88) is free of singularities for ground target viewing, but could conceivably be a problem

during the last 1,000 to 1,500 feet of travel during the rendezvous situation due to the singularity along the vehicle x-axis. However, this problem is easily remedied by yawing the vehicle slightly or by displacing the roll gimbal axis from the vehicle x-axis if further study shows this condition to be of real importance in an operational sense.

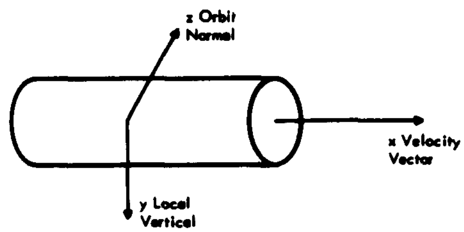


Figure 3-88. Vehicle Coordinate System

3.6.2 Attitude Control System Study Results

3.6.2.1 Fuel and Time Limitations

If a single gimbal were used and the vehicle rather than the roll gimbal rolled, then a fuel penalty is paid which is approximately 0.046 pound/target for a roll of 40 degrees in 204 seconds of time.

The fuel penalty isn't too great, but because of limitations on the star trackers of about 0.2 degree/second and 0.045 degree/second^2, the time of 204 seconds is exhorbitant if two targets close to each other are to be tracked.

If accelerations and velocity limitations are not considered, the 40-degree roll can be traversed in 15 seconds with a fuel cost of approximately 0.6 pound. In this case the fuel penalty is rather severe for several targets. In either case, because of time or fuel limitations, rolling of the vehicle is not desirable for terrestrial targets; rather driving the roll gimbal is recommended.

3.6.2.2 Counter-Oscillatory Movement

Based on assumptions about the vehicle moments of inertia along the x-axis, a study was performed to determine the counter-oscillatory movement of the spacecraft due to motions of the scanning mirrors when in the "boustophedon" auto scan modes. This rate was 0.6×10^{-4} degree/second when the mirror rate was 3 degrees/second and the acceleration was 1.2×10^{-4} degree/second.^{2} Neither this rate nor acceleration will cause the star trackers to loose lock-on, and the periodic displacement over 6 seconds is only 1.35 seconds of arc.

3.6.2.3 Vehicle Attitude Motion With Control System Turned Off

Assume

- I_{xx} = 8800 slug-feet^2
- I_{yy} = 21.500 slug-feet^2
- Angular rate limit 0.1 degree/second
- Gravity gradient is the only significant force acting on the vehicle.

The resulting motion is

ω_x = 0.1 degree/second

ω_y = 0.1 + 1.11 x 10^{-4} Δ t degree/second

ω = 0.1 - 1.11 x 10^{-4} Δ t degree/second

if Δt = 100 seconds, the maximum rate and displacement errors are

ω_x = 0.1 degree/second

ω_y = 0.111 degree/second

ω_z = 0.164 degree/second (considering an orbital rate of 0.0659 degree/second)

ϕ = 11 degrees

θ = 11.55 degrees

ψ = 17 degrees

The displacement errors are not troublesome, but the rate errors degrade the performance of the star tracker, even though it does not lose lock-on until a rate of 0.2 or 0.5 degree is reached.

Therefore, it is recommended that for target tracking, the attitude control system first null out the residual attitude control rates, using body mounted rate gyros, to at least 0.01 degree/second just prior to the tracking period. When time-to-go is zero, the attitude control system can be shut off. The disturbance accelerations will be small enough so that the ensuing rates will not degrade both the star tracker performance and the performance of the astronaut.

3.6.2.4 Fuel Requirements

The fuel required to maintain the x axis along the velocity vector and the y axis along the local vertical is shown in Figure 3-89. To maintain this attitude, body-mounted rate gyros, rate integrating gyros, horizon sensors and possibly a drift sight on the PTS will be required.

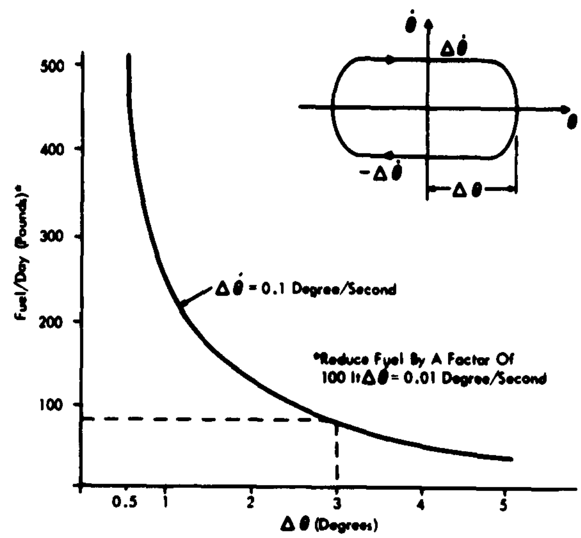


Figure 3-89. Attitude, Limit, Cycling, Fuel, Penalties

The recommendation based on this preliminary study indicates that a limit cycle of 3 degrees and 0.01 degree/second is satisfactory for IVSS. The fuel consumption is approximately 1 pound/day for continuous limit cycle operation.

3.6.3 Attitude References for PTS Pointing

A prime sensor for tracking several targets consecutively will be the star trackers that provide a long-term celestial reference for PTS pointing from target to target. To minimize alignment error between the celestial reference and the servo mounting plate of the PTS, the star trackers should be mounted on the PTS servo reference plate. The plate is external to the vehicle and covered with a shroud during launch. This mounting scheme will minimize erroneous updating of vehicle parameters and erroneous automatic pointing.

The other sensors, which include the inertial reference package and the horizon sensors, can be mounted elsewhere on the vehicle, providing the axes of mounting are parallel with both the chosen vehicle axis and the attitude control actuators. The alignment accuracy is not as stringent with these sensors as it is for the star trackers, since the former are basically used for vehicle alignment along the velocity vector and for initial pointing and tracking of single, isolated targets. In this case, static pointing errors are essentially eliminated by the astronaut.

3.6.4 Navigation Requirements

Simulation runs made on the 7090 computer showed that rms position and velocity errors of 250 feet and 4 feet/second are adequate to keep the angular rate errors to 0.02 percent.

If, for example, (1) the Gemini ground tracking network*(Figure 3-90) were used, (2) estimates of vehicle position and velocity were transmitted to the vehicle, and (3) the equations of motion were integrated, the resulting maximum position and velocity errors after the 30th orbit would be on the order of 360 feet and 0.1 feet/second (3 σ) along the major axis of the error ellipsoid.

Additional information regarding ground support operations is presented in Section 5.3.

Orbit Number / Site		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Cape Kennedy	•	-	69	68	44	-	-	-	-	-	-	-	-	-	45	68	69	69	52	-	-	-	-	-	-	-	-	-	-	40	69	69	65
Grand Bahama	•	-	23	69	49	-	-	-	-	-	-	-	-	-	57	69	67	68	68	-	-	-	-	-	-	-	-	-	14	66	69	67	65
Bermuda	•	-	65	38	-	-	-	-	-	-	-	-	-	-	55	66	67	58	-	-	-	-	-	-	-	-	-	-	23	62	67	65	33
Canary	•	-	-	-	-	-	-	-	-	-	-	39	52	69	69	67	32	-	-	-	-	-	-	-	-	-	58	69	68	69	58	-	-
Ascension Island		-	16	68	42	-	-	-	-	-	-	-	-	-	-	-	-	56	65	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Carnarvon	•	65	69	55	-	-	-	-	-	-	-	-	-	61	69	65	67	67	26	-	-	-	-	-	-	-	-	37	68	66	65	68	-
Hawaii	•	13	67	64	57	62	69	44	-	-	-	-	-	-	-	-	54	68	61	60	67	64	-	-	-	-	-	-	-	-	-	65	-
Pacific Ocean Ship	•	-	-	-	-	-	-	23	27	24	24	-	-	-	-	-	-	-	-	-	-	-	26	26	24	26	-	-	-	-	-	-	-
Guaymas		64	69	64	-	-	-	-	-	-	-	-	-	-	25	66	69	69	67	-	-	-	-	-	-	-	-	-	-	53	68	68	-
White Sands		35	39	31	-	-	-	-	-	-	-	-	-	-	-	19	38	36	-	-	-	-	-	-	-	-	-	-	-	-	33	-	-
Eglin AFB		41	38	-	-	-	-	-	-	-	-	-	-	-	26	40	40	30	-	-	-	-	-	-	-	-	-	-	-	36	41	39	-

*Command Site.

Notes: (1) Pacific Ocean Ship figures indicate of geocentric tracking arc for coverage above 5 degrees minimum elevation angle.

(2) Number of Observations Based on one observation every 6 seconds.

Figure 3-90. Coverage for an Assumed Tracking Net in Number of Observations

* "Gemini Ground System Compatibility Analysis Report," IBM Report No. 62-564-0146.

3.7 Error Analysis for Analog Instrumentation

This section presents an analysis of errors in the design approach for the analog instrumentation. These comments are pertinent in the discussion of error isolation in that the capability to evaluate IMC performance in this mode is contingent upon the ability of the system to maintain IMC in open loop or hands-off operation after the operator has ceased tracking.

There are two pertinent factors pertaining to the capability of the analog systems: (1) to provide the man with sufficient computational assistance to assure that he can track to criteria, and (2) to provide a system that will run open loop in post-track operation so that the closed-loop system may be evaluated.

The evaluation procedure has been to determine the required rate generation function for a flat earth model, to elect a candidate analog instrumentation, and to assess the drift rates which would be incurred by this system in open loop performance.

3.7.1 Derivation of Exact Tracking Function

The most general case of the required rates may be obtained from the configuration of Figure 3-91 where $\bar{R}$ and $\bar{V}$ are assumed to be misaligned by the angle β which is referenced in the roll plane to $\theta_R = 0$ by the angle $\delta\beta$.

The required rates as functions of V, H, θ_R, θ_P, β and $\delta\beta$ are developed as:

$$OT = \frac{H}{\cos\theta_R \cos\theta_P} \quad ; \quad OP = \frac{H}{\cos\theta_R}$$

$$\omega_{P_{OT}} = \frac{V_{Normal}}{OT} \quad \text{(in Plane OTP)}$$

In Plane OPT:

$$V_{Normal\ OT} = V \cos\beta \cos\theta_P - V \sin\theta_P \sin\beta\cos(\alpha_\beta - \theta_P)$$

$$\boxed{\omega_P = \frac{V}{H} \cos\theta_P \cos\theta_P \left[\cos\beta \cos\theta_P - \sin\theta_P \beta \cos(\alpha_\beta - \theta_R)\right]} \qquad (3\text{-}64)$$

$$\text{Also,} \quad \omega_{R_{OT}} = \frac{V_{Normal\ OP}}{OP} = \frac{V \sin\beta \sin(\alpha_\beta - \theta_R)}{OP}$$

$$\boxed{\omega_{R_{OT}} = \frac{V}{H} \cos\theta_R \sin\beta \sin(\alpha_\beta - \theta_R)} \qquad (3\text{-}65)$$

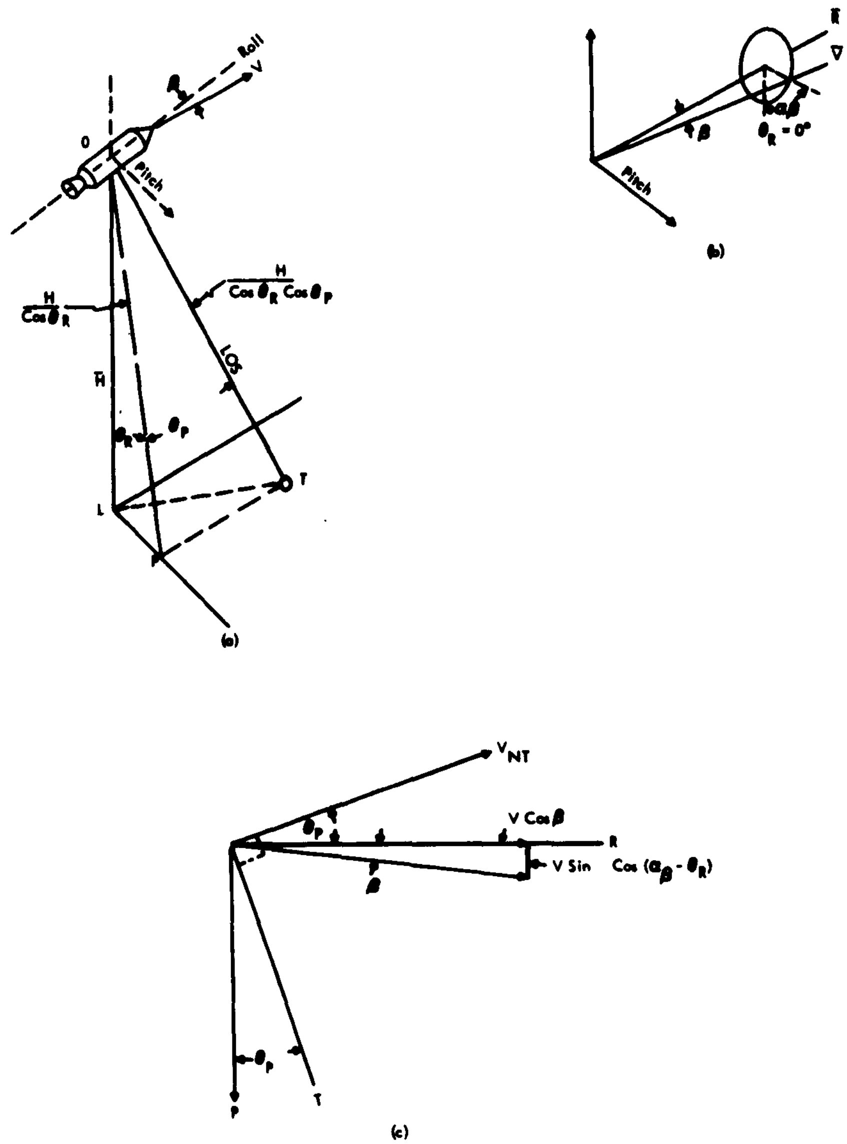


Figure 3-91. Geometry for Determining LOS Rate

For the case where the misalignment between the velocity vector and the roll axis is zero or small Equation (3-64) simplifies to:

$$\omega_{P_{OT}} = \frac{V}{H} = \cos^2 \theta_P \cos \theta_R \tag{3-66}$$

The candidate analog instrumentation which is recommended is one which resolves the hand control through the pitch and roll angles as in Equation (3-66) by employing the instrumentation shown in Figure 4-3.

For the pitch rate loop, consider that the tracking ends at time t_1 and that at θ_{P1} @ t_1, the generated pitch rate is exact by assuming the astronaut's capability to effect exact tracking. Then the hand control function $\omega_{HC} = f(\theta_R, \theta_P, \beta, \alpha_\beta, \omega_{P_1})$ is resolved through θ_P and θ_R so that:

$$\omega_{HC} \cos \theta_{R1} \cos^2 \theta_{P1} = \omega_{Exact} = \frac{V}{H} \cos \theta_{P1} \cos \theta_{R1}$$

$$\left[\cos \beta \cos \theta_{P1} - \sin \theta_{P1} \sin \beta \cos (\alpha_{\beta 1} - \theta_{R1})\right], \tag{3-67}$$

i.e.,

$$\omega_{HC} = \frac{V}{H \cos \theta_{P1}} \left[\cos \beta \cos \theta_{P1} - \sin \theta_{P1} \beta \sin \beta \cos (\alpha_\beta - \theta_{R1})\right]. \tag{3-68}$$

Now, if the loop is allowed to run open loop for Δt, the generated $\omega_{P_{OT}}$ at θ_{P2} and θ_{R2} is the ω_{HC} signal held and resolved through the updated angles.

$$\omega_{P_{OT(2)}} = \frac{\cos \theta_{R2} \cos^2 \theta_{P2} \cdot V}{H \cos \theta_{P1}} \left[\cos \beta_1 \cos \theta_{P1} - \sin \theta_{P1} \sin \beta \cos (\alpha_\beta - \theta_{R1})\right] \tag{3-69}$$

whereas, the exact rate at θ_{P2} should be (from the exact solution):

$$\omega_{P2} \text{ (exact)} = \frac{V}{H} \cos \theta_{P2} \cos \theta_{R2} \left[\cos_{\beta 2} \cos \theta_{P2} - \sin \theta_{P2} \sin \beta \cos (\alpha_{\beta 2}\ \theta_{R2})\right]. \tag{3-70}$$

The error in pitch rate at θ_{P2} is: Equation (3-70) minus Equation (3-69) and the decimal percent error in LOS rate is:

$$\text{decimal \% } e_{\omega_P} / \theta_{P2} = \frac{\text{Eq. (3-70) - Eq. (3-69)}}{\text{Eq. (3-70)}}$$

Substituting in the above:

$$\% e_{P} = \frac{\left\{\left[\cos\beta_2 \cos\theta_{P2} - \sin\theta_{P2}\sin\beta_2 \cos(\alpha_{\beta 2} - \theta_{R2})\right]\right.}{\cos\beta_2 \cos\theta_{P2} - \sin\theta_{P2}\sin\beta_2 \cos(\alpha_{\beta 2} - \theta_{R2})}$$

$$\frac{\left. - \frac{\cos\theta_{P2}}{\cos\theta_{P1}}\left[\cos\beta_1 \cos\theta_{P1} - \sin\theta_{P1}\sin\beta_1 \cos(\alpha_{\beta 1} - \theta_{R1})\right]\right\}}{\text{denominator}}$$

The following assumptions are made to obtain an estimate of the error:

- That $\cos(\alpha_\beta - \theta_R) = 1$ (i.e., worse case)
- That $\beta_2 \simeq \beta_1$ which states that the misalignment change between evaluation points is ignorable, which appears sound for small time intervals.

So that: $\% e_{\omega_{P1}}$ becomes:

$$\text{decimal } \% e_{P} = \frac{\left[\cos\beta\cos\theta_{P2} - \sin\theta_{P2}\sin\beta\right]}{\cos\beta\cos 0_{P2} - \sin\theta_{P2}\sin\beta} - \frac{\frac{\cos\theta_{P2}}{\cos\theta_{P1}}\left[\cos\beta\cos\theta_{P1} - \sin\theta_{P1}\sin\beta\right]}{\text{denominator}}$$

$$\% e_{\omega_P} = \left[\frac{\cos(\theta_{P2} + \beta) - \frac{\cos\theta_{P2}}{\cos\theta_{P1}}\cos(\theta_{P1} + \beta)}{\cos(\theta_{P2} + \beta)}\right] \times 10^2 \tag{3-71}$$

An additional assumption will be made in evaluating the error: that closed loop tracking will terminate at nadir, i.e., $\theta_{P1} = 0^\circ$. This is the optimum pitch angle to terminate track and commence open loop evaluation. At this point $\omega_P = \omega_{P_{max}}$ but $\dot{\omega}_P = 0$ so that the effect of the hold is maximized.

Therefore, Equation (3-71) reduces to:

$$\% e_{\omega_P} = \left[\frac{\cos(\theta_{P2} + \beta) - \cos\theta_{P2} \cdot \cos\beta}{\cos\beta}\right] \times 10^2 \tag{3-72}$$

From Equation (3-72) it is apparent that the accruing error in pitch rate due to this analog implementation is critically dependent on the initial misalignment vector β. As previously noted, with this candidate instrumentation, the rate generation by updating the command rate through the pitch and roll angles is precise (to the model) if β is zero.

Table 3-14 shows the percent error in pitch rate for increasing slant viewing angle from nadir (where open-loop tracking commences) for several initial misalignment angles. It is estimated that $\beta_{max} = 3^{\circ}$ since this is the maximum excursion of the attitude control limit cycle.

Table 3-14
PITCH PERCENT ANGULAR RATE ERROR

β: / $\% e\, \omega_P$	0.5°	1.0°	1.5°	2.0°	2.5°	3.0°
$\theta_{P2} = 1.0^{\circ}$	0.016	0.032	0.047	0.062	0.078	0.093
2.0°	0.031	0.062	0.093	0.123	0.153	0.184
3.0°	0.047	0.093	0.138	0.184	0.229	0.305
5.0°	0.076	0.153	0.229	0.304	0.381	0.457
7.0°	0.108	0.214	0.320	0.426	0.533	0.639
10.0°	0.153	0.304	0.456	0.607	0.759	0.911

3.7.2 Conclusion on Candidate Analog Instrumentation

The percent errors in the LOS rate shown in Table 3-14 are attributed only to computational error. To evaluate IMC achieved in this mode, the error in instrumentation and the error in photographic interpretation must be included. These sources have been previously discussed; however, the error contributed by the computational technique alone points out the constraint of maintaining a small misalignment angle β. The allowable angle θ_{P2}, which is the difference in pitch angle over which evaluation photographs are taken, is constrained by the desired percent IMC performance. From Table 3-14 for small β, it is apparent that θ_{P2} must be only a few degrees at maximum.

Table 3-15 gives the time approximate interval for evaluation as a function of θ_{P2}.

Table 3-15
AVAILABLE TIME FOR ANALOG TRACKING EVALUATION

$_{P2}$(degrees)	Δt (sec)
1	0.67
2	1.34
3	2.01
4	2.68
5	3.34

Δ t has been evaluated for the flat earth model at the 160 n mi altitude and θ_{P1} = 0 degrees, that is, evaluation begins at nadir.

To maintain β as a small angle, say less than one degree, it may be possible to constrain the cycling of the attitude control system as some predictable function of drift time so that the misalignment angle is passing through zero at the time of nadir. Sophistication of the evaluation techniques and possible modifications to the instrumentation scheme are areas recommended for additional study.

Small alignment can be obtained in the analog mode by employing the driftmeter reticle of the PTS to determine the ground track relative to the target. The accuracy associated with this mode is about C. 5 degree.

4.0 System Synthesis

The purpose of this section is to present the rationale used to synthesize and define the IVSS. The design criteria presented immediately below combine the analytical results of the functional requirements, Section 3, with the results of the elemental simulations. The portions of the IVSS that are specifically addressed are:

- Servo-computer modes of operation
- Optical system synthesis
- Candidate servo systems
- Data management philosophy
- Displays and controls.

4.1 IVSS Design Criteria

Table 4-1 categorizes the salient criteria that affect the design of the IVSS. These criteria are reflected in the discussions in Section 4 and the functional descriptions in Section 5.

Table 4-1

IVSS DESIGN CRITERIA

Design Parameter	Design Criteria	Source
Man's Discrete Pointing Performance	Will center crosshairs over target to within 15 arc second (one-sigma error)	ESS
Man's Tracking Performance	Will track to within 2 seconds/second better than 50 percent of time (ESS error - 0.8 arc second/second)	ESS
Range of Magnification	Man's performance will improve with magnification up to at least 100X	ESS
PTS Aperture	D ≈ 2.3 inches for visual tracking D ≈ 8 inches for photo optical evaluation of P-1 D ≈ 12 to 14 inches for 2nd part P-3 requirement*	Section 3.2.1
PTS Focal Length	F ≈ 36 inches for P-1 and P-3 F ≈ 45 to 60 inches for 2nd part P-3 requirement	Section 3.2.1

Table 4-1. IVSS Design Criteria (cont)

Design Parameter	Design Criteria	Source
PTS Interior Volume	6 feet along longitudinal axis 3 feet radially 1 foot width	USAF SSD
Maximum Field of View	7.5 degrees for acquisition of ground targets 12 degrees for acquisition of space targets	Sections 3.1.1.1 and 3.1.2.1
Minimum Photograph** Sampling Time	T ≈ 1.0 second for 0.2 percent IMC T ≈ 6.0 seconds for 0.05 percent IMC (Determination at 30 degrees sighting angle)	Section 3.2.1
Servo Requirements	See Table 3-10	Section 3.3
Maximum Digital Computation Cycle (T)	Computer Cycle ≈2 seconds	Section 3.4

* For trade-off analysis purpose only

** T = Sampling time between photographs

4.2 IVSS Modes of Operation

During the course of the study three important modes of operation have been investigated:

- Primary Digital Tracking Mode
  - Minimum rate prediction techniques.
  - Extended rate prediction techniques.
- Analog Tracking Mode
  - No rate prediction technique.
  - Minimum rate prediction technique.
  - Extended rate prediction technique.
- Extended Capabilities Digital Tracking Mode

4.2.1 Primary Digital Tracking Mode

The primary function of this mode of operation is to compute the line of sight rate based on body axis and gimbal axis rates measured while the operator is tracking a terrestrial or space target.

The orbital ephemeris for the vehicle will not be updated with fix information and consequently the computed LOS rate will be correct only for the target being tracked and for a short time thereafter if the operator relinquishes control. The computer requirements for both the Primary and Extended capability modes are shown in Table 5-14.

4.2.1.1 Minimum Rate Prediction Techniques

In this mode, the target will be initially located within the field of view of the PTS by computing pointing angles based on the extrapolated position and velocity of the vehicle and the stored position of the target. Once the target is centered within the field of view of the sensor, a rate prediction computation for the pitch gimbal only will be used to aid the operator in tracking.

In effect, the operator will only have to compensate for the error functions that accrue due to the inaccuracies in knowledge of the various sources of pointing and tracking errors described in Section 3.4.

The basic equation used is:

$$\dot{\theta} \quad \frac{V}{H} \cos^2\theta \quad \cos\theta$$

where $\frac{V}{H}$ represents orbital rate and is generated by the operator.

The geometry is shown in Figure 4-1.

A more detailed discussion of this minimum-rate prediction scheme can be found in Section 3.7, Volume III, entitled Error Analysis for Analog Instrumentation. It should be pointed out, however, that precise alignment between the relative velocity vector and the roll gimbal axis should be maintained to keep the LOS rate error below 0.02 percent. If the PTS is used as a driftmeter to align the vehicle to the ground track to within an accuracy of 0.05 degrees, the man can relinquish control for approximately 1 second before the LOS rate error exceeds 0.02 percent.

In addition to the LOS rate computation, the following functions are performed in the Primary Digital Tracking mode:

- Pointing-angle commands
- V_N vector computation
- Latitude and longitude of ground track
- Time to go before target may be observed
- Sun angles
- Tracking time
- Ground target geographical determination
- Automatic scanning
- Space target tracking
- Align and calibrate by pointing to preselected stars

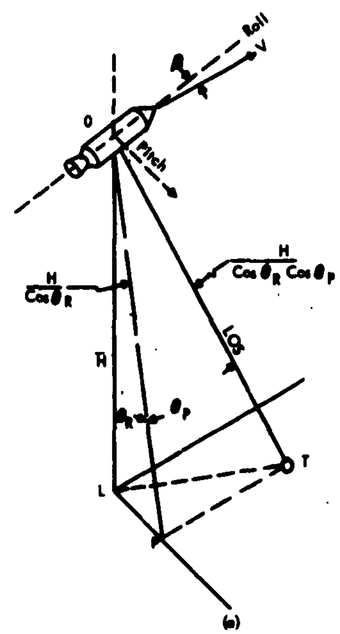


Figure 4-1. Geometry for Minimum-Rate Prediction Scheme

Figure 4-9 is a detailed math flow diagram showing the logical operations and computations required to implement the above. An explanation of the functions contained in the math flow diagrams is contained in Section 4.2.4, where these computations plus a few others make up the extended capability mode.

The servo computer mode functional diagram is shown in Figure 4-2. The servo design is the same as that used in the Extended Capabilities Digital Tracking mode and is a position device with precise digital feedback.

Under normal circumstances, when the target is being acquired, the computer merely sends pointing angles to the digital interface where a first-order hold is performed and sampling occurs at a lower rate. The hand control then serves to put increments of position into the system if the operator so wishes. Note that for the roll channel, the gain term is modified by the cos θ so the same deflection of the hand control will result in the same image rate regardless of pitch gimbal position.

When rate prediction is utilized, the computer stores the last value of rate and position and adds the hand control deflection, modified by the appropriate gain terms, to the last value of rate ($\dot{\theta}_0$). Therefore, the hand control pulse applies an increment of velocity and an increment of acceleration. To assist the operator in tracking the target using the pitch channel. For the roll channel the hand control supplies increments of acceleration or constant velocity changes to assist the operator in this channel.

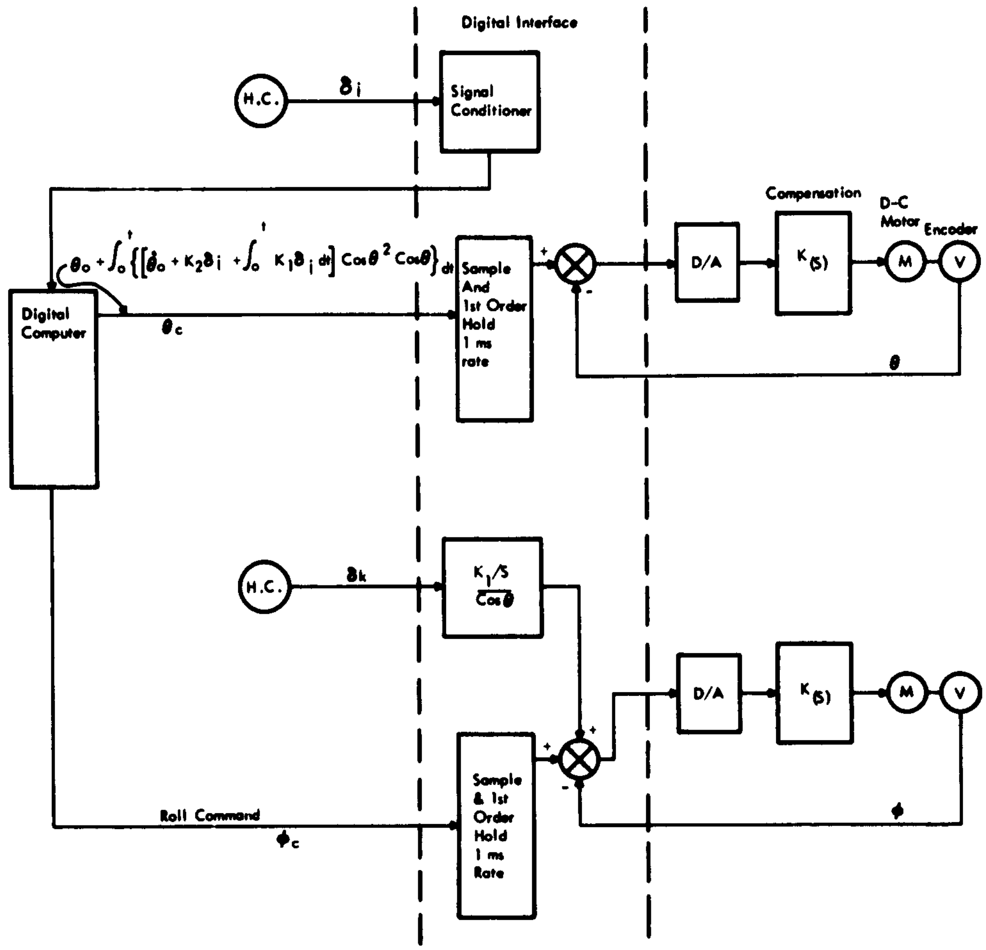


Figure 4-2. Primary Digital Tracking Servo Computer Mode

To date, the extended rate prediction schemes have been assessed to the point of functional equation development. The relative importance of image motion sensitivity to errors in the vehicle state parameters is discussed in Section 3.4. A concept instrumentation is presented and discussed for the analog case in Section 4.2.2.3.

4.2.2 Analog Tracking Mode

4.2.2.1 No Rate Prediction Technique

The simplest analog tracking mode that was considered was a rate servo with no prediction capability (Figure 4-3). Each output of the hand controller (representing acceleration) is routed through the $\left[\frac{K_1}{S} + K_2\right]$ transfer function and then to a voltage-controlled oscillator (VCO) which generates a frequency (ω_θ , ω_ϕ) keyed to the angular rate $\dot{\theta}$, $\dot{\phi}$. This frequency is compared to a similar frequency generated in the feedback

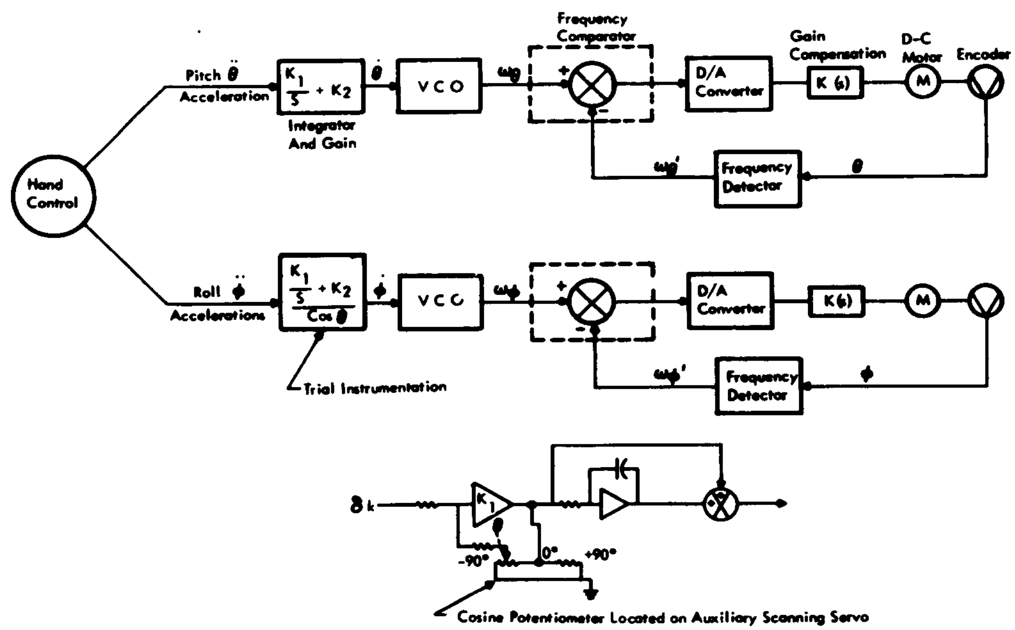


Figure 4-3. Servo Computer Without Rate Prediction

loop by observing and operating on the least-significant bit of the digital encoder. The digital output of the frequency comparator represents the servo error signal, which is converted to an analog voltage operated on by a lead/lag network and routed to the d-c amplifier and motor.

In this mode of operation, the operator must arrest apparent image motion while keeping the target centered near the crosshairs with virtually no help. This task is quite difficult, especially about the acceleration maximum near 30 degrees obliquity.

This mode of operation requires the operator to be constantly inserting acceleration pulses to keep up with the changing angular rate of the line of sight. If during this tracking time the operator were to remove his hand from the controller, the values of $\dot{\theta}$ or $\dot{\phi}$ routed to the gimbal servos would remain constant at the last value, while the real-world LOS rate would be changing resulting in severe image motion. This, of course, implies that only short open-loop tracking times are available for experiment evaluation purposes.

The magnitude of the open-loop image motion can be better appreciated by the following brief analysis. Consider that no errors exist while the astronaut is tracking, and assume that the roll axis is aligned very closely to the velocity vector; then the motion for an in-plane target is given approximately by

$$\dot{\theta} = \frac{V}{H} \cos^2\theta$$

When the astronaut releases the hand controller, the variation due to changing angular rates (in percent IMC versus time) is given by

$$\%\text{IMC} = \frac{100\Delta\dot{\theta}}{\theta} = 100\frac{V}{H}\sin^2\theta\Big]\ \Delta t$$

which is plotted in Figure 4-4.

Thus at a 5 degree sighting angle, θ , it would take 0.05 second for the rate to build up to 0.02 percent, and 0.23 second for 0.1 percent IMC.

4.2.2.2 Minimum Rate Prediction

A minimum-rate prediction scheme, as discussed in Section 4.2.1 for the primary digital tracking mode, can be used here to alleviate the short observation times for post-track evaluation.

An error analysis considering only the misalignment error between the velocity vector and the roll axis is presented in Section 3.7 of Volume III.

Figure 4-5 is a functional sketch of this servo computer mode with minimum rate prediction.

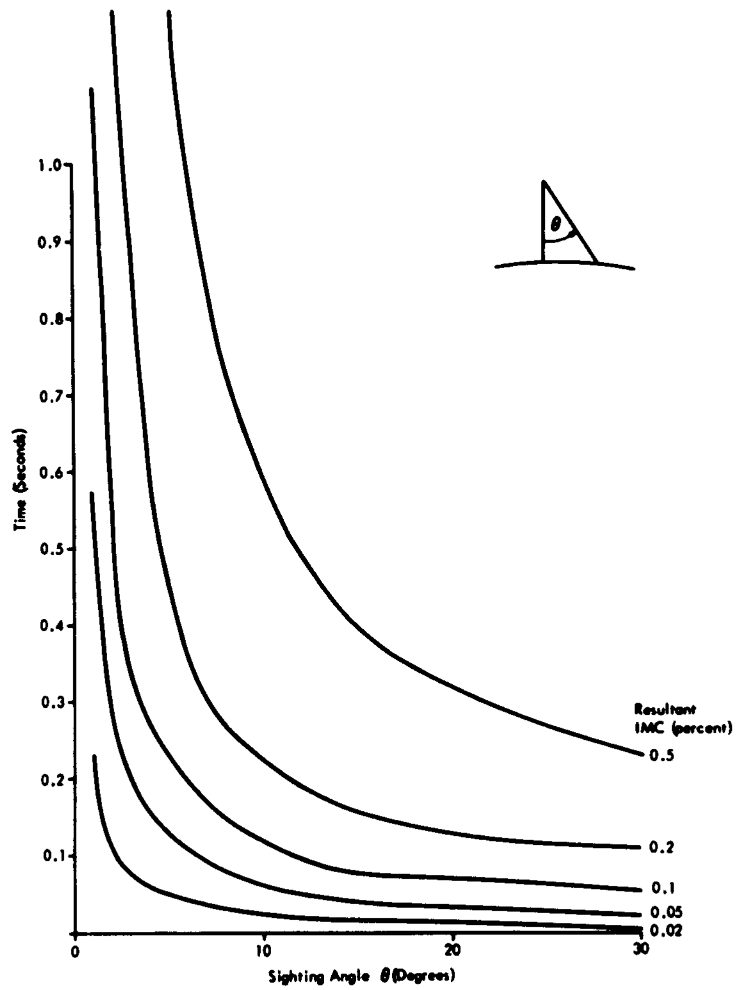


Figure 4-4. IMC Degradation Times for "Hands-Off" Tracking With No Prediction

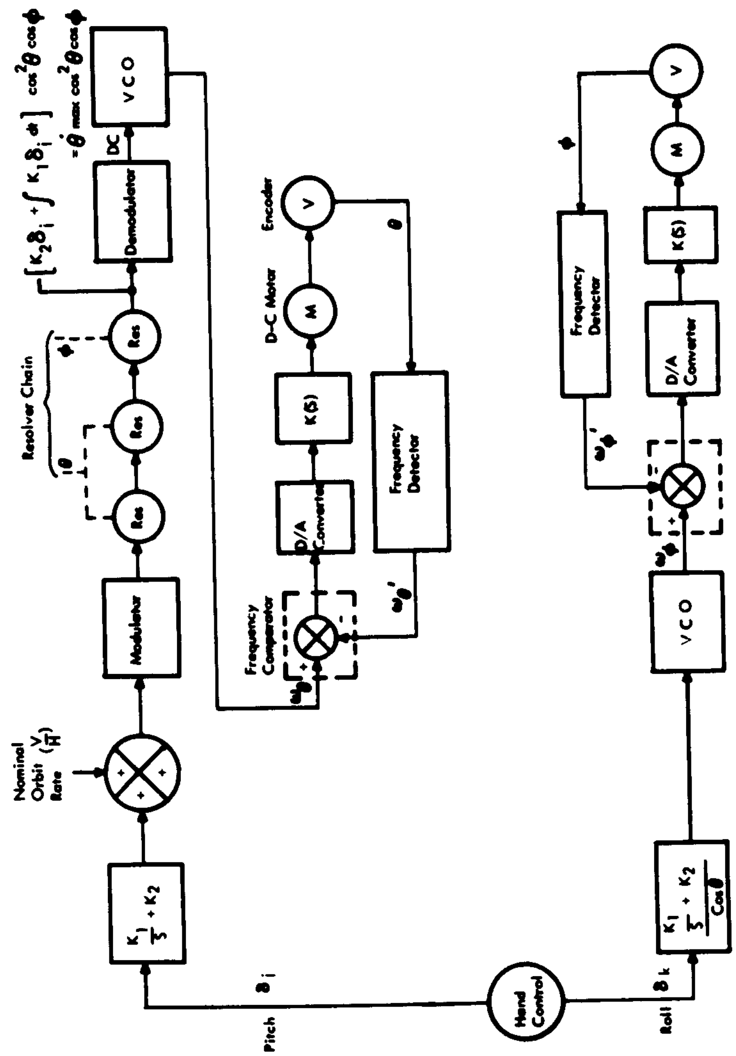


Figure 4-5. Servo Computer With Minimum Rate Prediction

4.2.2.3 Extended Rate Prediction

To minimize the effects of misalignment and other error sources, a more sophisticated rate prediction scheme employing certain data filtering concepts (see Section 3.4) may be required. The time requirement for post-tracking is 5 seconds to allow evaluation down to 0.05 percent IMC.

An example of the form of regenerative error function computation which might be implemented to extend the time of post-track evaluation is shown in the equations below for the coordinate system of Figure 4-6.

The desired or required angular rates of the LOS relative to the vehicle are a function of the position and velocity of the satellite, the attitude and attitude rates of the vehicle, and the pitch and roll angles of the LOS. The sensitivities of the pitch and roll rates to uncertainties in the above quantities are summarized in Table 4-2.

A list of state variables tentatively recommended for inclusion in an IMC filtering concept are contained in Table 4-3.

These states are not necessarily optimum from an implementation viewpoint and require more detailed trade-off studies to consider the difficulty of computational implementation for analog and digital systems vs the IMC performance limitations imposed by the exlusion of the filter term.

Figure 4-7 shows a conceptual instrumentation using the hand control outputs. The equations implemented for the pitch channel utilize the five recommended state variables shown in Table 4-3.

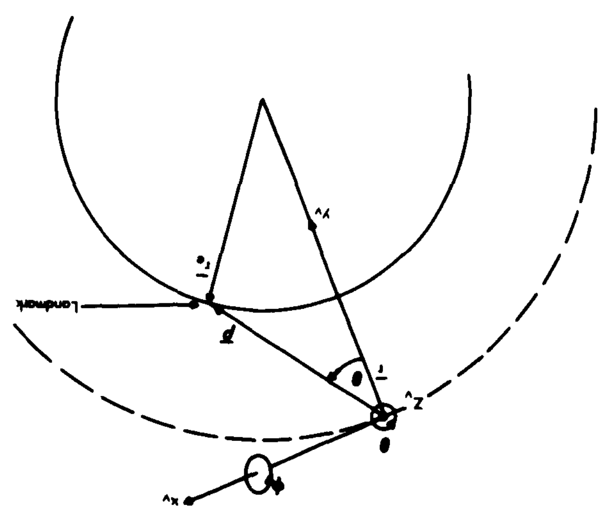


Figure 4-6. Geometry for Error Sensitivity Matrix

Table 4-2

RELATIVE IMPORTANCE OF IMC SENSITIVITY PARAMETERS

Parameter	1σ Error	Roll Rate Error		Pitch Rate Error	
		Functional Representation	Typical Value** (sec/sec)	Functional Representation	Typical Value** (sec/sec)
X	1350 ft	$\frac{-V_r}{\rho^2}\sin\phi\tan\theta\,\delta X_v$	0 (Approx.)	$-\left(\frac{V_\phi\cos\theta + V_r\cos\phi\sin\theta}{\rho^2}\right)\sin\theta\,\delta X_v$	1.4*
Y	1800 ft	$\frac{-V_r}{\rho^2}\sin\phi\cos\theta\,\delta Y_v$	0 (Approx.)	$-\left(\frac{V_\theta\cos\theta + V_r\cos\phi\sin\theta}{\rho^2}\right)\cos\phi\cos\phi Y_v$	5.8
Z	1200 ft	$\frac{-V_r\sin^2\phi}{\rho^2}$	0 (Approx.)	$-\left(\frac{V\theta\cos\theta + V_r\cos\phi\sin\theta}{\rho^2}\right)\sin\phi\cos\theta\,\delta Z_v$	1.0
$\dot{X}$	85 fps	0	0	$\frac{-\cos\theta}{\rho}\,\delta\dot{X}_v$	12.8
$\dot{Y}$	85 fps	$\frac{\sin\phi}{\rho\cos\theta}\,\delta\dot{Y}_v$	4.2	$+\frac{\cos\phi\sin\theta}{\rho}\,\delta\dot{Y}_v$	6.0*
$\dot{Z}$	85 fps	$-\frac{\cos\phi}{\rho\cos\theta}\,\delta\dot{Z}_v$	12.8	$\frac{\sin\phi\sin\theta}{\rho}\,\delta\dot{Z}_v$	1.7*
	$\pm 10\ \widehat{sec}$	$(\phi\sin\theta + \frac{V_\theta}{r}\cos\theta\sin\phi)\frac{\delta\theta}{\cos\theta}$	0.004	$(\frac{V_\theta}{\rho}\sin\theta - \frac{V_r}{\rho}\cos\theta\cos\phi)\,\delta\theta$	0.09*
	$\pm 10\ \widehat{sec}$	$(\frac{V_\theta}{r}\sin\theta - \frac{V_r}{\rho})\frac{\cos\phi}{\cos\theta}\,\delta\phi$	0.006	$(\frac{V_r}{\rho}\sin\phi\sin\theta - \frac{V_\theta}{r}\sin\phi)\,\delta\phi$	0.01
ω_x	$\pm 36\ \widehat{sec}$/sec	$-\delta\omega_{x_v}$	36	0	0
ω_y	$\pm 36\ \widehat{sec}$/sec	$\cos\phi\tan\theta\,\delta\omega_{y_v}$	21.6*	$-\sin\phi\,\delta\omega_{y_v}$	10.8
ω_z	$\pm 36\ \widehat{sec}$/sec	$\sin\phi\tan\theta\,\delta\omega_{z_v}$	5.76*	$\cos\phi\,\delta\omega_{z_v}$	35
θ_x	720 $\widehat{sec}$	$-\frac{V_r\cos\phi}{\rho\cos\theta}\,\delta\theta_{x_v}$	0	$\frac{V_r}{\rho}\sin\phi\sin\theta\,\delta\omega_{x_v}$	0
θ_y	720 $\widehat{sec}$	$-\frac{V_\theta\cos\phi}{\rho\cos\theta}\,\delta\theta_{y_v}$	13.6	$\frac{V_\theta}{\rho}\sin\phi\sin\theta\,\delta\theta_{y_v}$	1.7*
θ_z	720 $\widehat{sec}$	$-\frac{V_\theta\sin\phi}{\rho\cos\theta}\,\delta\theta_{z_v}$	3.6	$\frac{1}{\rho}(V_r\cos\theta - V_\theta\cos\phi\sin\theta)\,\delta\theta_{z_v}$	5.6*

* Denotes sensitivity. Vanishes monotonically as sighting angle approaches nadir.

** Landmark 60 n mi out of orbital plane. The orbit is taken as circular at a 200 n mi altitude. Value is taken to be the maximum for sighting angles below -30° degrees.

Table 4-3
RECOMMENDED STATE VARIABLE FOR IMC FILTER

Roll Rate		Pitch Rate	
Horizontal Cross Velocity	$\dot{z}$	Altitude	Y
Vehicle Roll Rate	ω_x	Horizontal In Plane Velocity	$\dot{X}$
Vehicle Yaw Rate	ω_y	Vehicle Yaw Rate	ω_y
Vehicle Yaw Attitude	θ_y	Vehicle Pitch Rate	ω_z
		Vehicle Pitch Attitude	θ_z

$$\dot{\theta}_c = K_o \delta \dot{\theta}_c + \frac{V}{H} \cos^2\theta + \left[K_1 \cos^2\theta + K_2 + K_3 \sin\theta \cos\theta + K_4 \cos^4\theta\right] \int d\dot{\theta}_c$$

where:

$\dot{\theta}_c$ = computed pitch gimbal torquing rate

$K_o \delta \dot{\theta}_c$ = error in pitch gimbal rate (from hand control)

$K_1 \cos^2\theta \int \delta\dot{\theta}_c$ = error function for ($\delta \dot{x}$) velocity error along track

$K_2 \int \delta\dot{\theta}_c$ = error function for ($\delta\omega_z$) altitude pitch rates

$K_3 \sin\theta \cos\theta \int \delta\dot{\theta}_c$ = error function for ($\delta\theta_z$) altitude error about pitch axis

$K_4 \cos^4\theta \int \delta\dot{\theta}_c$ = error function for (δ_y) error in altitude

The values of the constants, K_n, would be set proportional to their expected error magnitudes. If attitude rates were to be accurately measured directly (i. e., from rate gyros), the attitude error function constants would be set equal to zero.

This mode of operation provides the flexibility to vary the gains of the error functions to be used in orbit. By observation of the error functions, it can be seen that the rate of change of the functions at different sighting angles may be a very powerful clue as to the nature of the error in the system. The advisability of varying the gains of the regenerative terms as a function of the rate of change of the error and the pitch angle will have to be investigated in the next phase.

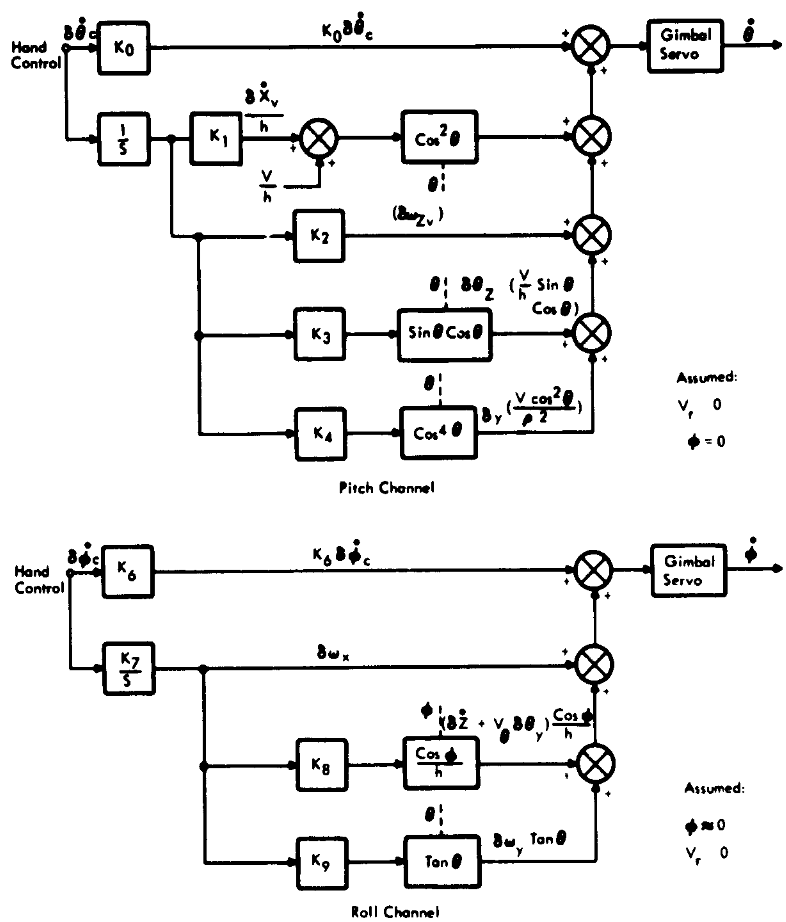


Figure 4-7. Analog Extended-Rate Prediction Filter

4.2.3 Extended Capability Digital Tracking Mode

The major difference between the extended capability digital tracking mode, (Figure 4-8) and the primary digital tracking mode (Figure 4-9) is that in the former the vehicle orbit ephemeris is updated by processing tracking data using (1) a Kalman filtering procedure, and (2) precise attitude information obtained from multiple star sights or some other precise attitude reference. This operation is based on (1) estimates of vehicle position and velocity, and (2) a covariance matrix of estimates of position and velocity uncertainties periodically obtained from the ground.

Vehicle equations of motion containing oblateness and drag terms are integrated in earth-centered inertial coordinates until observations on the known ground targets are to begin. Pointing angles are then computed to direct the LOS to the computed target position.

Assuming that the vehicle attitude is known precisely in inertial space and that the target location is known precisely, the major discrepancies between the observed and computed pointing angles at a given instant in time will be due to differences between computed and true vehicle positions and volocities. The Kalman filtering procedure is used to compute the position and velocity of the vehicle from successive LOS corrections, based on observations made on the tracking scope.

The servo-computer functional flow diagram is essentially the same as that for the primary digital mode (Figure 4-2) except the hand control signals add directly into the volumes of the gimbal angles coming from the computer.

The form of the ahnd control signlas after shaping are as follows:

Pitch gimbal error: $\delta j \left[\frac{K_1}{S}\right]$

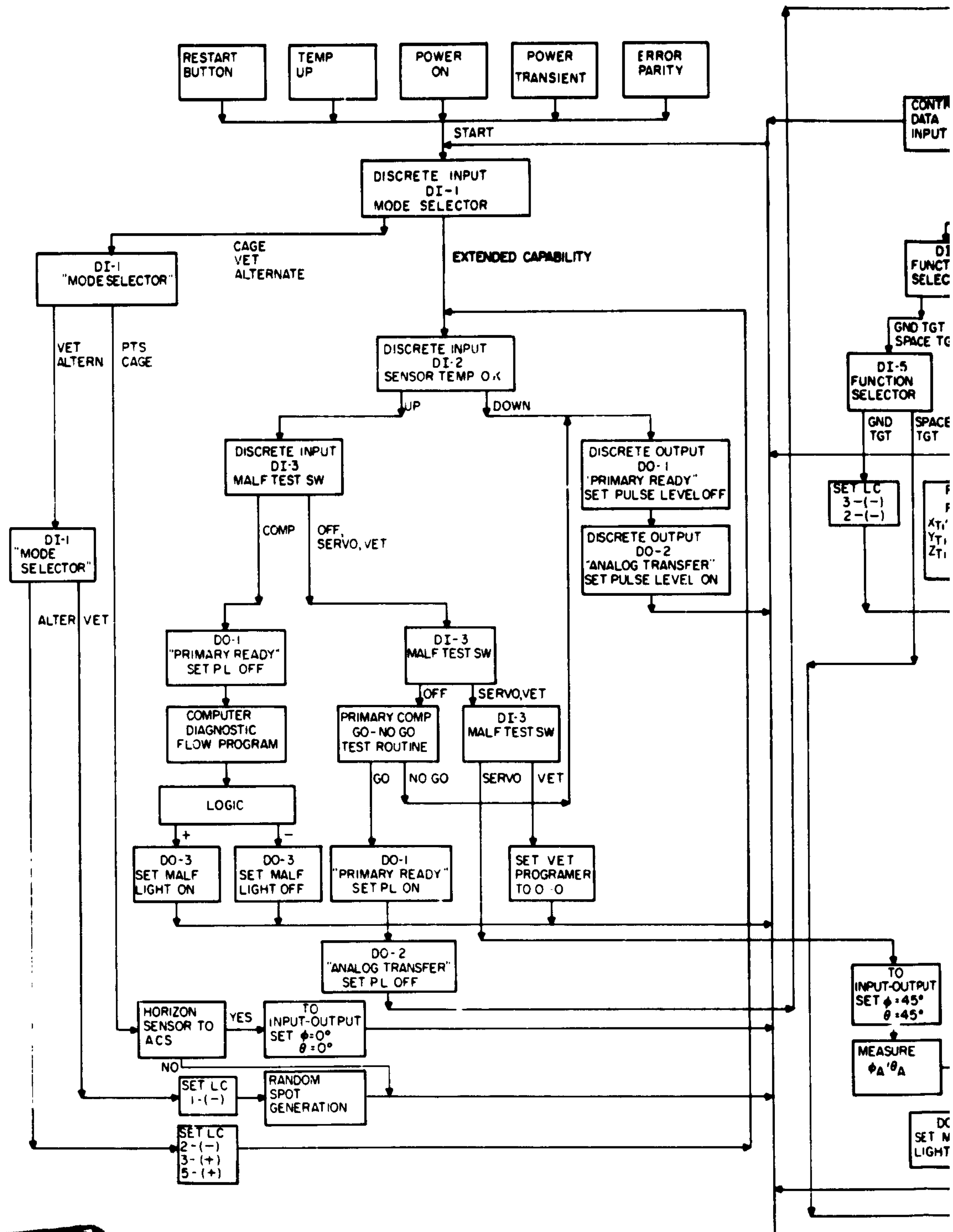
Roll gimbal error: $\delta k \left[\frac{K_1}{S \cos\theta}\right]$

For positive fixing purposes where the ephemeris is updated, each rate pulse of the hand controller represents position increments after integration.

4.2.4 IVSS Extended Capability Digital Math Flow Description

The following description refers to the detailed math flow diagrams for the extended capability mode (Figure 4-8). A complete list of math flow symbols for the diagrams is given in Table 4-4.

I-1 START UP & MODE CONTROL



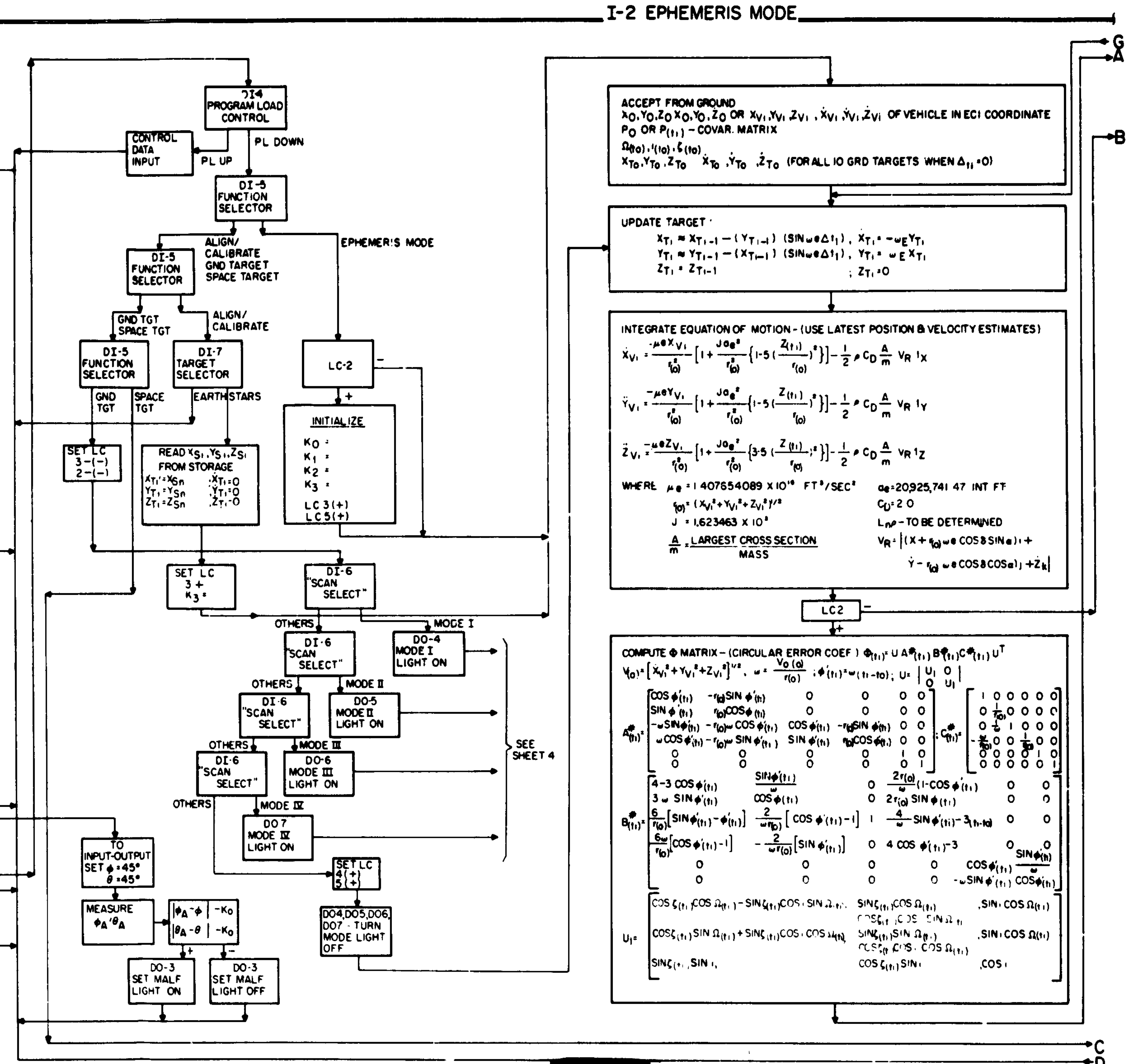
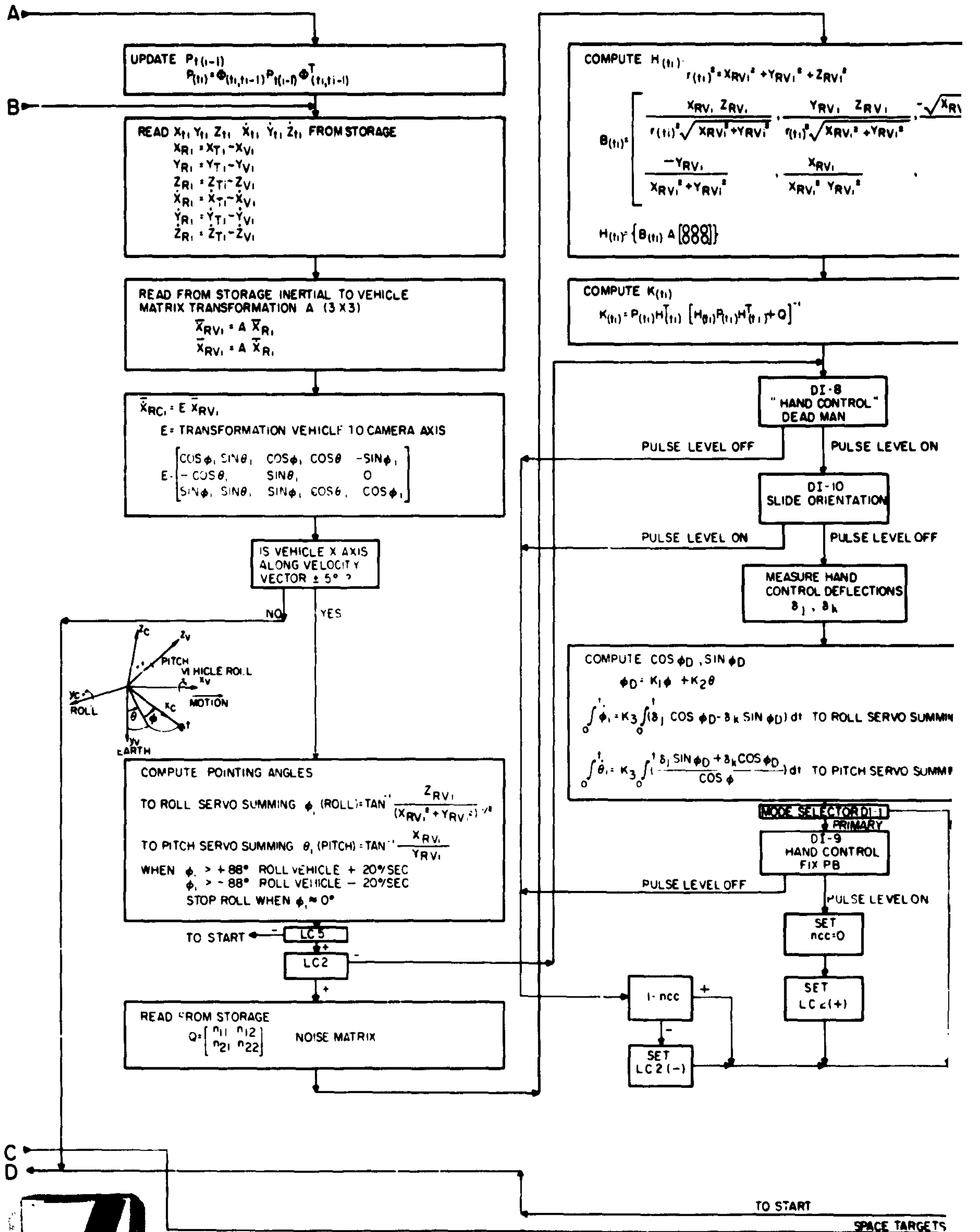


Figure 4-8. IVSS Extended Capability Digital System Math Flow (Sheet 1 of 4)

I-2 (cont.) EPHEMERIS MODE



I-3 EPHEMERIS MODE

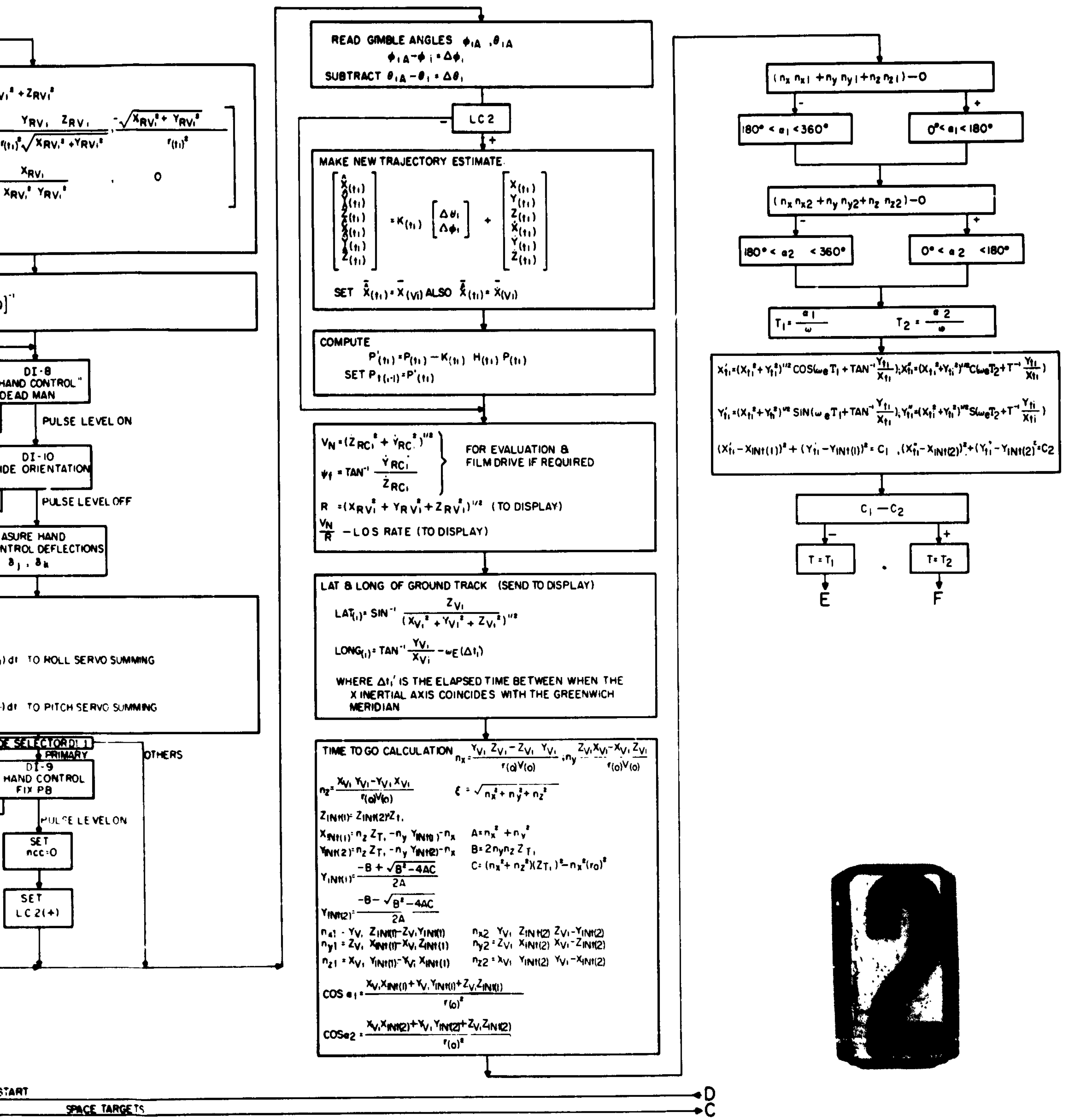
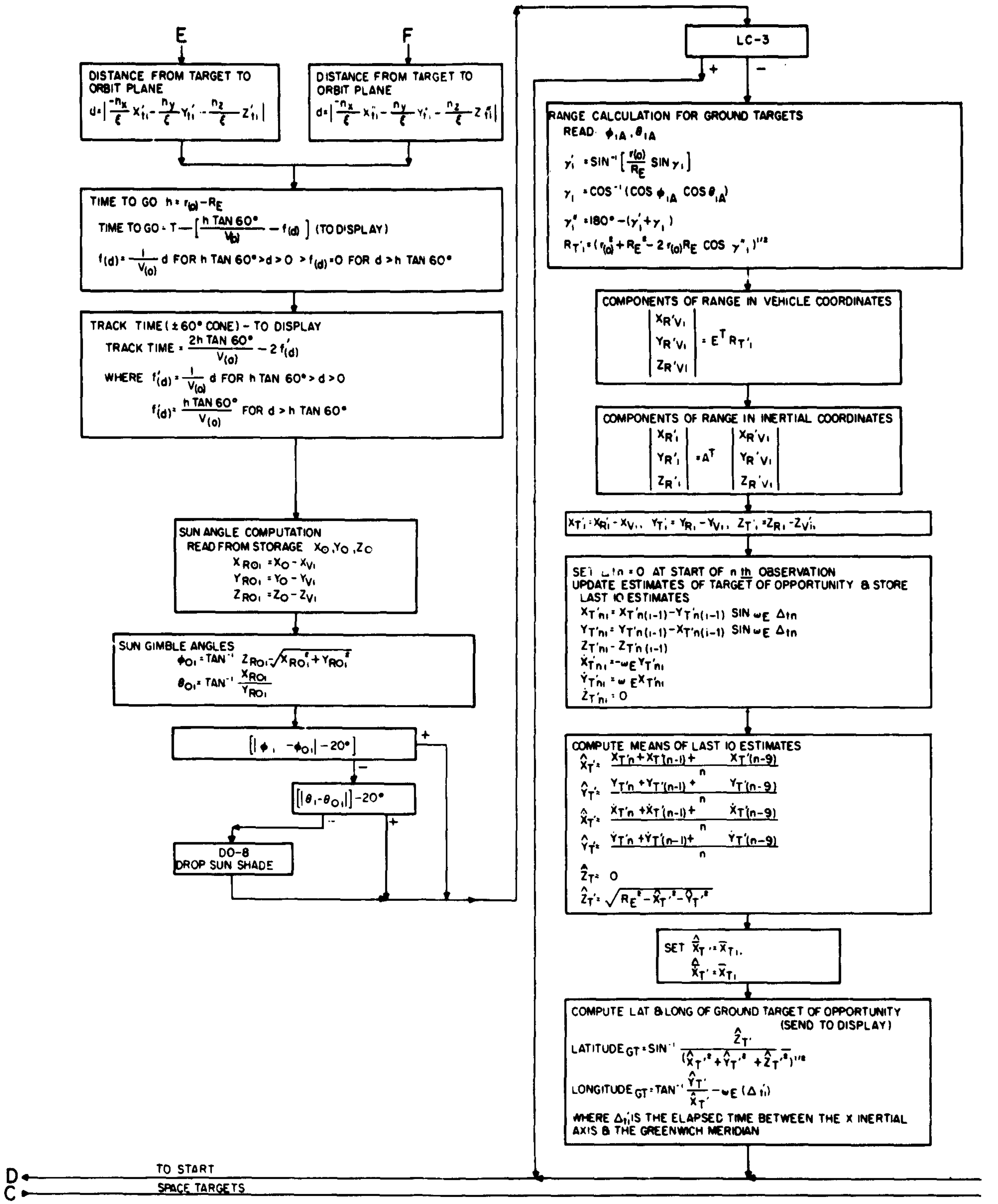


Figure 4-8. IVSS Extended Capability Digital System Math Flow (Sheet 2 of 4)

I-4 PRIMARY-EPHEMERIS MODE & GROUND TARGETS



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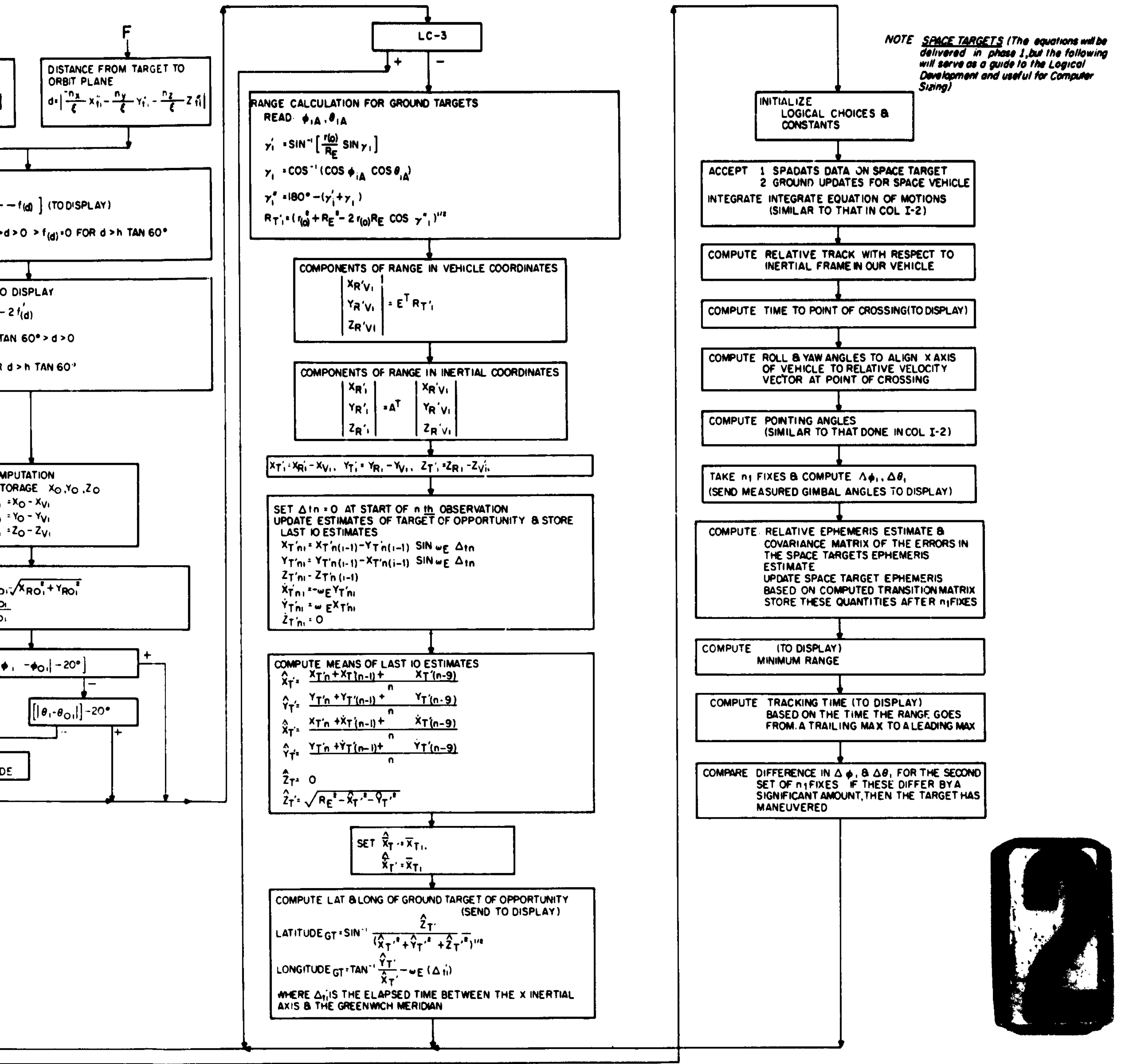
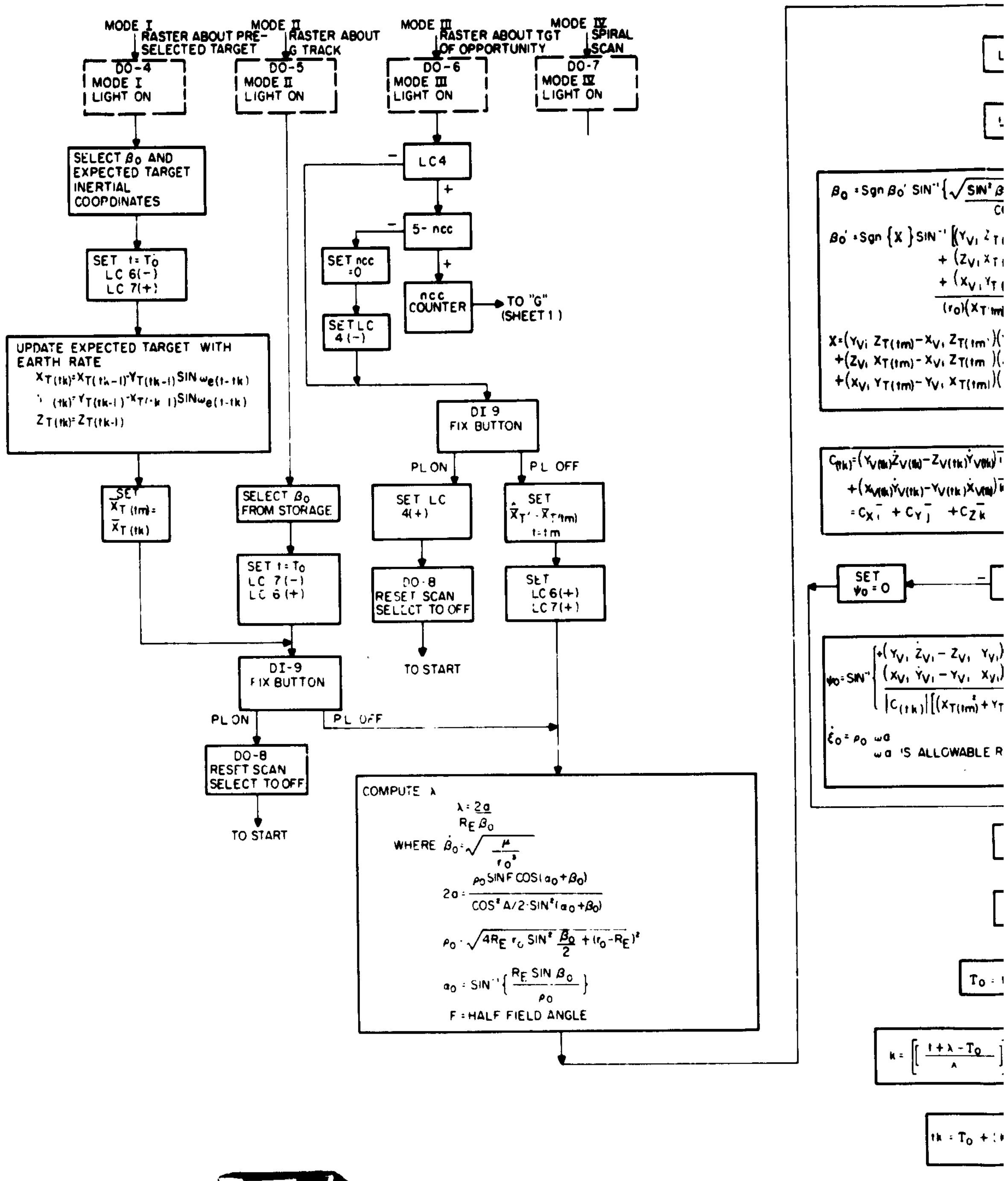


Figure 4-8. IVSS Extended Capability Digital System Math Flow (Sheet 3 of 4)

I-6 AUTO SCAN MODE



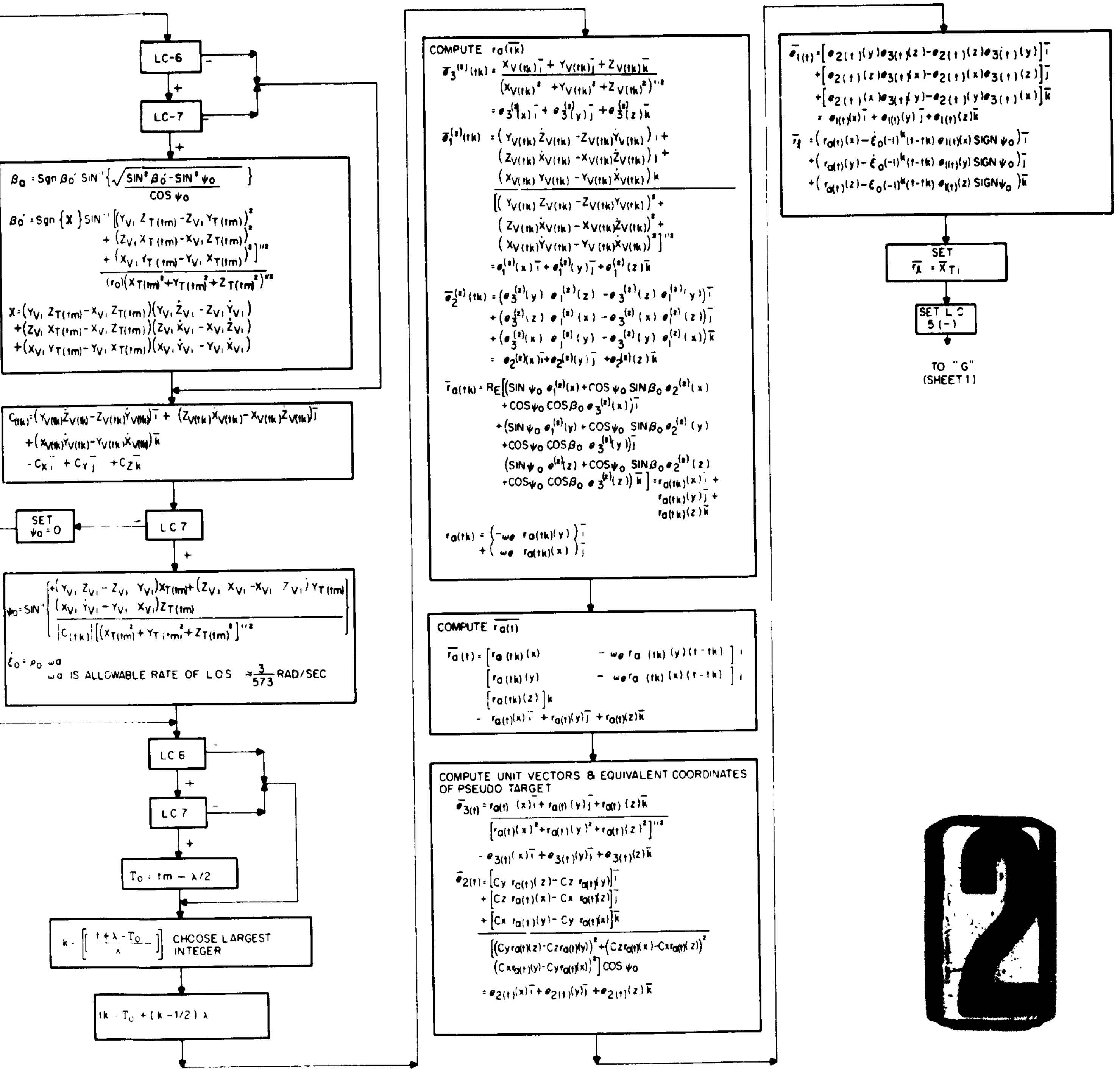
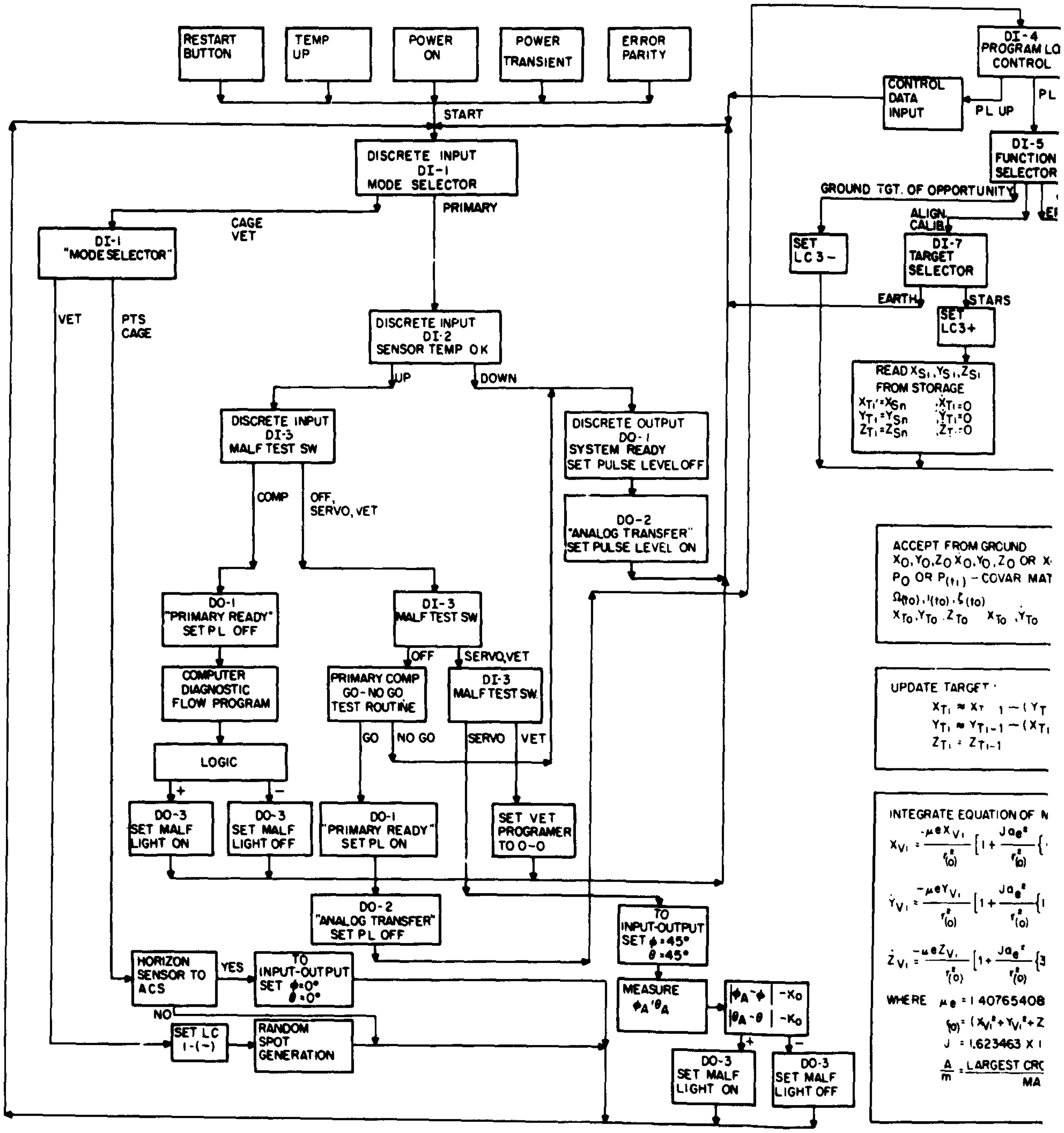


Figure 4-8. IVSS Extended Capability Digital System Math Flow (Sheet 4 of 4)



RESTART BUTTON
TEMP UP
POWER ON
POWER TRANSIENT
ERROR PARITY
START
DISCRETE INPUT DI-1 MODE SELECTOR
PRIMARY
CAGE VET
DI-1 "MODE SELECTOR"
VET
PTS CAGE
DISCRETE INPUT DI-2 SENSOR TEMP OK
UP
DOWN
DISCRETE INPUT DI-3 MALF TEST SW
COMP
OFF, SERVO, VET
DISCRETE OUTPUT DO-1 SYSTEM READY SET PULSE LEVEL OFF
DO-2 "ANALOG TRANSFER" SET PULSE LEVEL ON
DO-1 "PRIMARY READY" SET PL OFF
DI-3 MALF TEST SW
OFF
SERVO, VET
COMPUTER DIAGNOSTIC FLOW PROGRAM
PRIMARY COMP GO-NO GO TEST ROUTINE
DI-3 MALF TEST SW
GO
NO GO
SERVO
VET
LOGIC
DO-3 SET MALF LIGHT ON
DO-3 SET MALF LIGHT OFF
DO-1 "PRIMARY READY" SET PL ON
SET VET PROGRAMER TO 0-0
DO-2 "ANALOG TRANSFER" SET PL OFF
TO INPUT-OUTPUT SET φ=45° θ=45°
HORIZON SENSOR TO ACS
YES
TO INPUT-OUTPUT SET φ=0° θ=0°
NO
MEASURE φA, θA
SET LC 1-(-)
RANDOM SPOT GENERATION
DO-3 SET MALF LIGHT ON
DO-3 SET MALF LIGHT OFF
DI-4 PROGRAM LO CONTROL
CONTROL DATA INPUT
PL UP
PL
DI-5 FUNCTION SELECTOR
GROUND TGT. OF OPPORTUNITY
ALIGN CALIB.
SET LC3-
DI-7 TARGET SELECTOR
EARTH
STARS
SET LC3+
READ XS1, YS1, ZS1 FROM STORAGE
ACCEPT FROM GROUND
UPDATE TARGET
INTEGRATE EQUATION OF
WHERE μe = 1.40765408
J = 1.623463 X
A/m = LARGEST CR

7

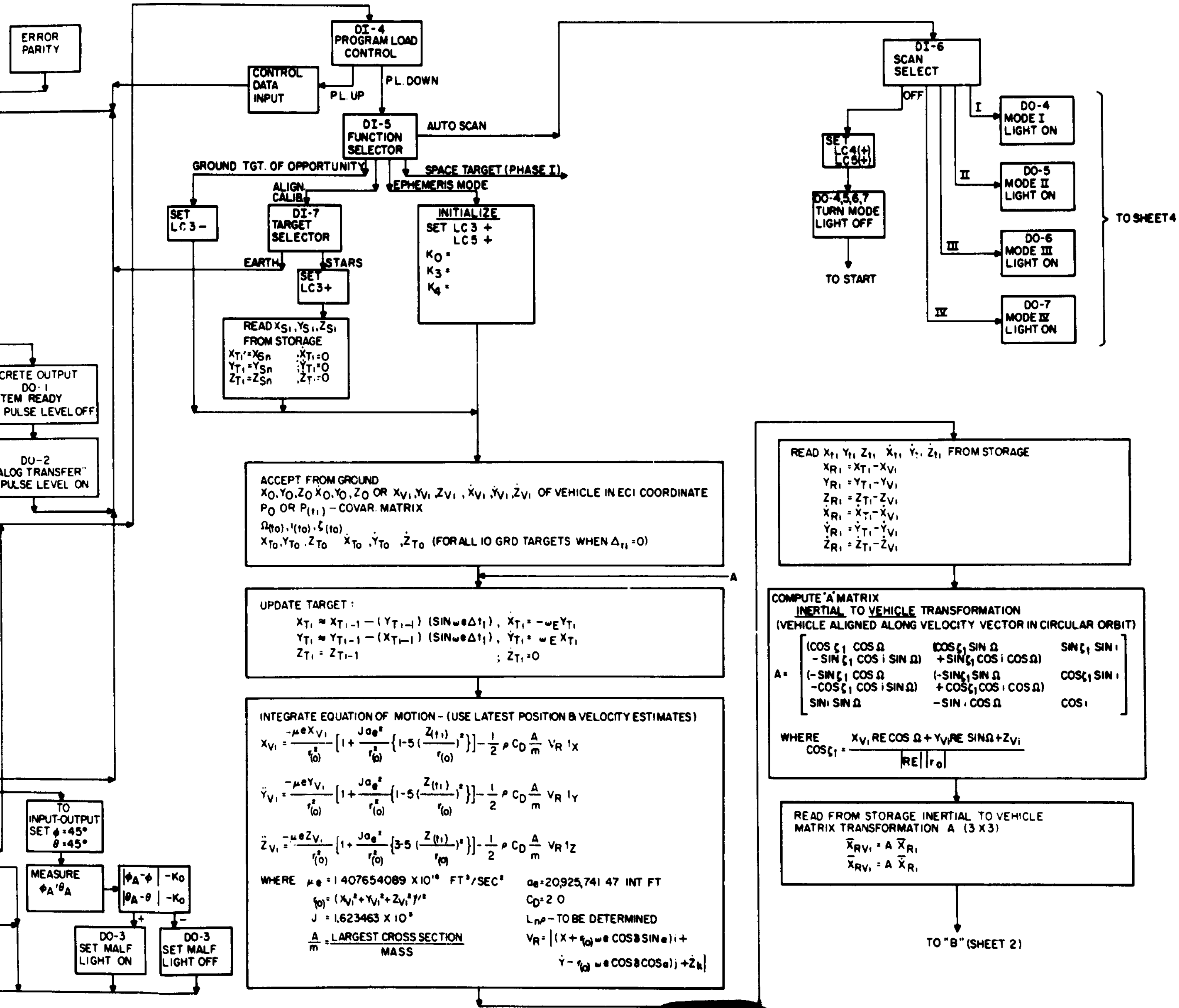
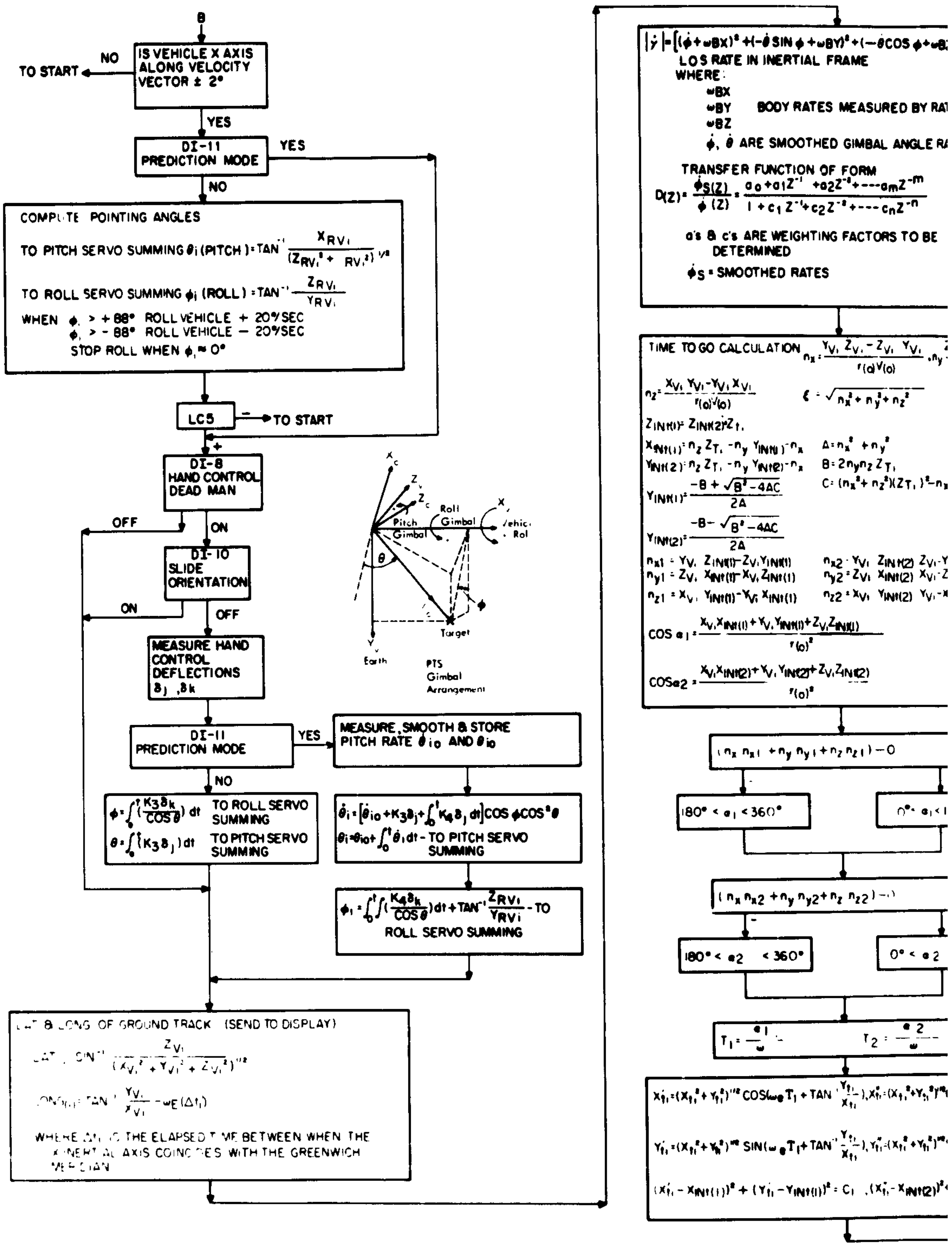


Figure 4-9. IVSS Primary Digital Mode Math Flow (Sheet 1 of 3)



B
IS VEHICLE X AXIS ALONG VELOCITY VECTOR ± 2°
NO
TO START
YES
DI-11 PREDICTION MODE
YES
NO
COMPUTE POINTING ANGLES
TO PITCH SERVO SUMMING
TO ROLL SERVO SUMMING
ROLL VEHICLE + 20°/SEC
ROLL VEHICLE − 20°/SEC
STOP ROLL WHEN
LC5
TO START
DI-8 HAND CONTROL DEAD MAN
OFF
ON
DI-10 SLIDE ORIENTATION
ON
OFF
MEASURE HAND CONTROL DEFLECTIONS
DI-11 PREDICTION MODE
YES
NO
MEASURE, SMOOTH & STORE PITCH RATE
TO ROLL SERVO SUMMING
TO PITCH SERVO SUMMING
TO PITCH SERVO SUMMING
ROLL SERVO SUMMING
Roll Gimbal
Pitch Gimbal
Vehicle Roll
Target
Earth
PTS Gimbal Arrangement
LAT & LONG OF GROUND TRACK (SEND TO DISPLAY)
WHERE Δt IS THE ELAPSED TIME BETWEEN WHEN THE INERTIAL AXIS COINCIDES WITH THE GREENWICH MERIDIAN
LOS RATE IN INERTIAL FRAME
WHERE:
BODY RATES MEASURED BY RA
ARE SMOOTHED GIMBAL ANGLE RA
TRANSFER FUNCTION OF FORM
a's & c's ARE WEIGHTING FACTORS TO BE DETERMINED
SMOOTHED RATES
TIME TO GO CALCULATION

7

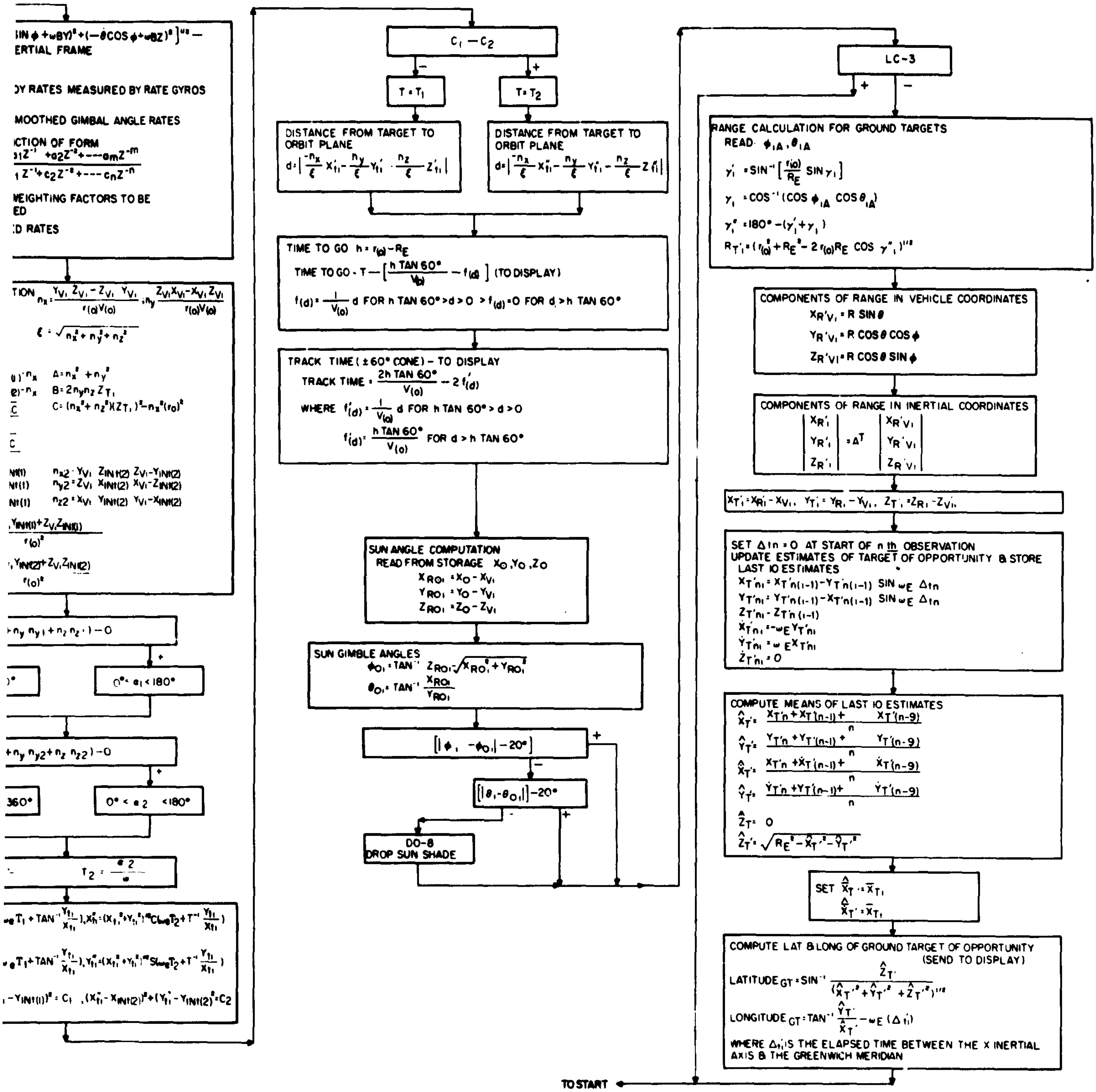
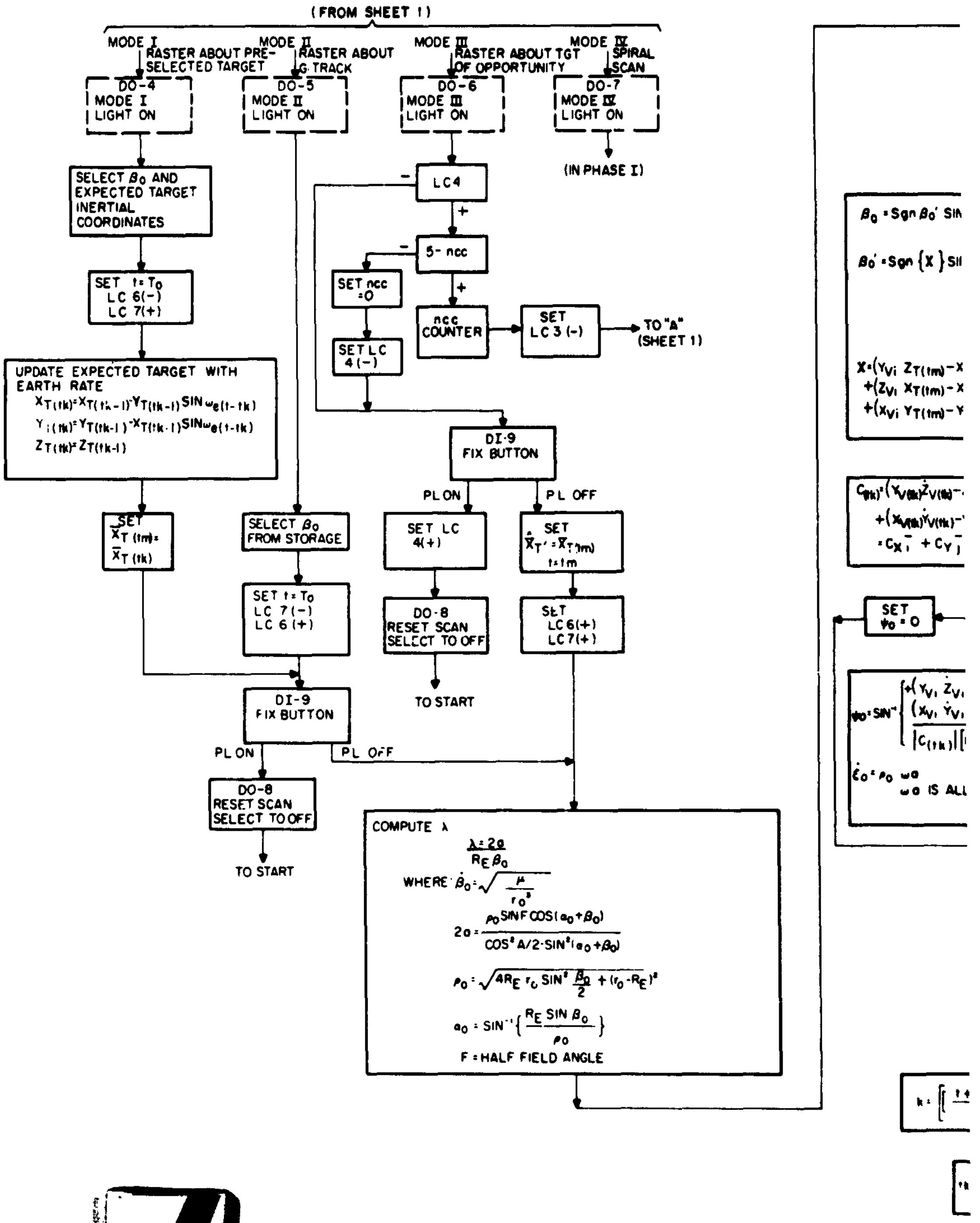


Figure 4-9. IVSS Primary Digital Mode Math Flow (Sheet 2 of 3)


(FROM SHEET 1)
MODE I
RASTER ABOUT PRE-SELECTED TARGET
MODE II
RASTER ABOUT G. TRACK
MODE III
RASTER ABOUT TGT OF OPPORTUNITY
MODE IV
SPIRAL SCAN
DO-4 MODE I LIGHT ON
DO-5 MODE II LIGHT ON
DO-6 MODE III LIGHT ON
DO-7 MODE IV LIGHT ON
(IN PHASE I)
SELECT β0 AND EXPECTED TARGET INERTIAL COORDINATES
LC4
5- ncc
SET ncc =0
SET LC 4(-)
ncc COUNTER
SET LC 3 (-)
TO "A" (SHEET 1)
SET t=T0 LC 6(-) LC 7(+)
UPDATE EXPECTED TARGET WITH EARTH RATE
DI-9 FIX BUTTON
PL ON
PL OFF
SET LC 4(+)
DO-8 RESET SCAN SELECT TO OFF
TO START
SET LC6(+) LC7(+)
SELECT β0 FROM STORAGE
SET t=T0 LC 7(-) LC 6(+)
COMPUTE λ
WHERE
F = HALF FIELD ANGLE
SET ψ0 = 0
IS ALL

7

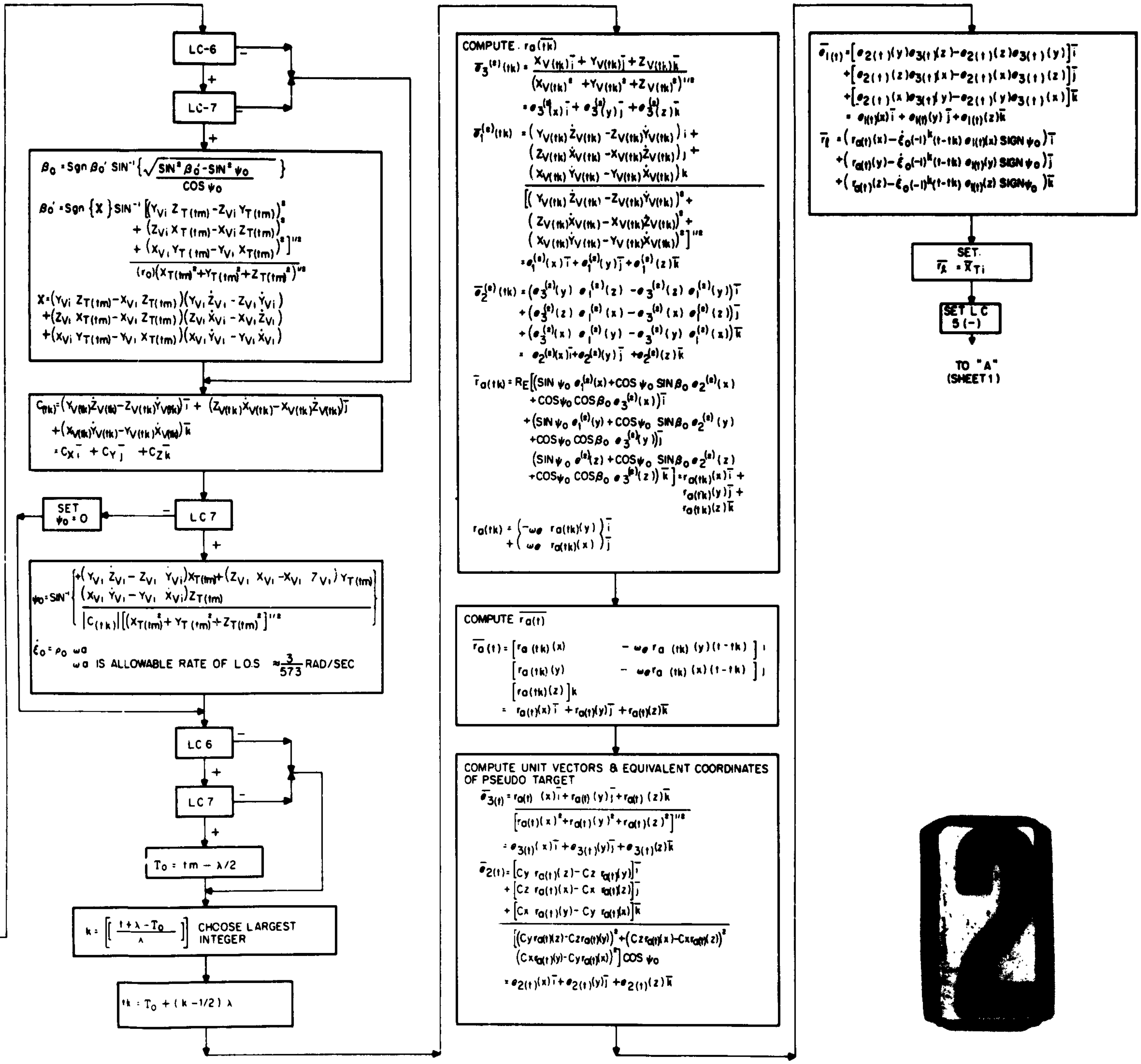


Figure 4-9. IVSS Primary Digital Mode Math Flow (Sheet 3 of 3)

Table 4-4
IVSS MATH FLOW SYMBOL LIST

A	Inertial to vehicle matrix transformation
A^T	A transpose
$\frac{A}{m}$	Largest cross-sectional area divided by the mass of vehicle
$A\#_{(ti)}$	Component matrices for transition matrix updating
a	Semimajor axes of ground projection in auto scan mode
$B_{(ti)}$	Observational matrix in inertial frame
$B\#_{(ti)}$	Component matrices for transition matrix updating
C_1	Distance between target and vehicle at intersection 1
C_2	Distance between target and vehicle at intersection 2
$C\#_{(ti)}$	Component matrices for transition matrix updating
C_D	Coefficient of drag
D_O	Discrete output
D_1	Discrete input
d	Distance from target to orbit plane
E	Vehicle to camera axis matrix transformation
E^T	E transpose
ECI	Earth-centered inertial
$f_{(d)}$	Function used to determine time-to-go
$f'_{(d)}$	Function used to determine track time
$H_{(ti)}$	Observation matrix vehicle frame
h	Altitude of vehicle above earth
$i_{(to)}$	Initial inclination of orbit
J	Oblateness term
K_O	Allowable angular error for servo test
K_1	Derotation roll gain
K_2	Derotation pitch gain
K_3	Hand control rate gain
K_{ti}	Filter weighting matrix
LC	Logical choice
$LAT_{(i)}$	Geocentric latitude of vehicle

Table 4-4 IVSS Math Flow Symbol List (cont)

$LONG_{(i)}$	Longitude of vehicle
LAT GT	Geocentric latitude of ground target
LONG GT	Longitude of ground target
n_x, n_y, n_z	Normalized components of normal-to-orbit plane in ECI coordinates
n_{x1}, n_{y1}, n_{z1}	Normal components of plane formed by vehicle position vector and first intersection vector
n_{x2}, n_{y2}, n_{z2}	Normal components of plane formed by vehicle position vector and second intersection vector
P_o	Initial covariance matrix
$P_{t(i)}$	Updated covariance at ith instant
$P'_{(ti)}$	Updated covariance matrix based on fixes
Q	Noise covariance matrix
R_E	Earth equatorial radius
R	Range from vehicle to target
$R_{T'i}$	Range to target for the ground target mode
$\bar{r}_e$	Pseudo target ECI coordinates in auto scon mode
r_o	Geocentric radius of vehicle
T_1	Time-to-go to first intersection point
T_2	Time-to-go to second intersection point
Δ_{t1}	Update increment time reference
Δ_{tn}	Time reference used to update target of opportunity
Δ_{ti}	The elapsed time at ith instant between the inertial x axis and the Greenwich meridian
U	Component matrices for transition matrix updating
$V_{(o)}$	Magnitude of vehicle velocity
V_R, l_x, l_y, l_z	Factors used in computing acceleration due to air drag
$X_{Ti}, \dot{X}_{Ti}$, $Y_{Ti}, \dot{Y}_{Ti}$, Z_{Ti}, Z_{Ti}	Target position and rate at ith instant in ECI coordinates

Table 4-4 IVSS Math Flow Symbol List (cont)

X_{SN}, Y_{SN}, Z_{SN}	Inertial star positions normalized
$X_o\ \dot{X}_o$, $Y_o\ \dot{Y}_o$, $Z_o\ \dot{Z}_o$	Initial vehicle position and velocity in ECI coordinates
$\ddot{X}_{Vi}, \dot{X}_{Vi}, X_{Vi}$, $\ddot{Y}_{Vi}, \dot{Y}_{Vi}, Y_{Vi}$, $\ddot{Z}_{Vi}, \dot{Z}_{Vi}, Z_{Vi}$	Vehicle accelerations, velocities, and positions in ECI coordinates at ith instant
X_{To}, Y_{To}, Z_{To}, $\dot{X}_{To}$, $\dot{Y}_{To}$, $\dot{Z}_{To}$	Initial target positions and velocities in ECI coordinates
$X_{Ri}, \dot{X}_{Ri}$, $Y_{Ri}, \dot{Y}_{Ri}$, $Z_{Ri}, \dot{Z}_{Ri}$	Relative position and velocities in ECI coordinates
$X'_{Ti}, Y'_{Ti}, Z'_{Ti}$	Updated target coordinates T_1 seconds later
$X''_{Ti}, Y''_{Ti}, Z''_{Ti}$	Updated target coordinates T_2 seconds later
$X_{\odot}, Y_{\odot}, Z_{\odot}$	Position of sun reference to ECI coordinates
$\hat{X}_{(ti)}, \hat{Y}_{(ti)}, \hat{Z}_{(ti)}$, $\hat{\dot{X}}_{(ti)}, \hat{\dot{Y}}_{(ti)}, \hat{\dot{Z}}_{(ti)}$	Estimated vehicle ephemeris with respect to ECI coordinates
$X_{INt(1)}, Y_{INt(1)}, Z_{INt(1)}$	First intersection of ground track with target latitude circle
$X_{INt(2)}, Y_{INt(2)}, Z_{INt(2)}$	Second intersection of ground track with target latitude circle
$X_{R\odot i}, Y_{R\odot i}, Z_{R\odot i}$	Relative position between vehicle and sun in ECI coordinates
$X_{R'Vi}, Y_{R'Vi}, Z_{R'Vi}$	Components of target in vehicle coordinates
$X_{R'i}, Y_{R'i}, Z_{R'i}$	Components of target in ECI coordinates
$X_{T'ni}, Y_{T'ni}, Z_{T'ni}$, $\dot{X}_{T'ni}, \dot{Y}_{T'ni}, \dot{Z}_{T'ni}$	Target ECI coordinates for n^{th} observation at ith instant (both position and velocity)
$\hat{X}_{T'}, \hat{Y}_{T'}, \hat{Z}_{T'}$, $\hat{\dot{X}}_{T'}, \hat{\dot{Y}}_{T'}, \hat{\dot{Z}}_{T'}$	Best estimate of target ECI coordinates at end of n^{th} observation

Table 4-4 IVSS Math Flow Symbol List (cont)

α_1	Geocentric angle between vehicle position vector and first intersection vector
α_2	Geocentric angle between vehicle position vector and second intersection vector
ϕ_{iA}	Actual roll gimbal angle measured
θ_{iA}	Actual pitch gimbal angle measured
$\phi_i , \dot{\phi}_i$	Computed roll angle and rates at ith instant
$\theta_i , \dot{\theta}_i$	Computed pitch angle and rates at ith instant
$\Delta\phi_i$	Difference between actual and computed roll angle
$\Delta\theta_i$	Difference between actual and computed pitch angle
$\phi_{\odot i}$	Roll angle to point to sun
$\theta_{\odot i}$	Pitch angle to point to sun
ϕ_D	Angle of derotation
δ_j	Up and down hand control deflections
δ_k	Left and right hand control deflections
γ'_i	Angle between LOS and target vector in target vehicle plane
γ_i	Angle between local vertical and LOS in target vehicle plane
γ''_i	Geocentric angle between target and vehicle for the ground target mode
ψ_f	Angle of V_N in camera measured from Z_C $\perp$ to LOS
$\zeta_{(to)}$	Initial argument of perigee
$\Omega_{(to)}$	Initial longitude of the ascending mode
ω_e	Earth rate
ρ	Atmospheric density function
Φ	Transition matrix-based on circular error coefficient
μ_e	Earth gravitational constant
$\cdot$	A dot over a quantity indicates differentation with respect to time
$\_$	A bar over a symbol indicates a vector quantity
$\lvert \quad \rvert$	Indicates the absolute value of the quantity
$[\quad]$	Indicates an (n x m) matrix
$[\quad]^T$	Indicates the transpose of the matrix
$[\quad]^{-1}$	Indicates the inverse of the matrix

4.2.4.1 Start Up and Mode Control

In this porition of the program, all logical choices and constants are initialized to ready the balance of the program for the following selected modes of operation:

(a) Extended capability

(b) Alternate

(c) Visual evaluation tracker (VET)

(d) PTS cage.

4.2.4.1.1 Extended Mode — This mode encompasses the following functions, which will be detailed later:

- Ephemeris updating
- Pointing angle commands
- $\overline{V}_N$ - vector computation
- LOS rate computation
- Latitude and longitude of ground track
- Time-to-go before target may be observed
- Sun angles
- Tracking time
- Ground target geographical determination
- Auto scan
- Space target tracking
- Align and calibrate by pointing to preselected stars
- Miscellaneous outputs to system

4.2.4.1.2 Alternate Mode - This mode includes all of the above except ephemeris updates of ground and space targets.

In this mode, instead of taking fixes, the astronaut relies upon previous ground estimates of his ephemeris and the updating of vehicle position and velocity by continuous integration of the equations of motion.

4.2.4.1.3 The Visual Evaluation Tracker Mode - VET is detailed in Volume IV. In summary, the computer will perform switching to allow a preprogrammed generation of a spot of light to be presented to the operator, who in turn will use the hand control to keep the crosshairs on the spot.

4.2.4.1.4 The PTS Cage Mode - This mode is utilized to align the x axis of the vehicle to the relative velocity vector (or the approximate orbit plane). This is of particular importance when a star tracker is not used as a reference, and the PTS must be pointed relative to a rotating coordinate system defined by horizon sensors for pitch and roll attitude. This mode also serves as another gross check on the scanning servos, since the command will be 0 degrees in both pitch and roll during this operation.

4.2.4.1.5 Malfunction Indications — This section contains a malfunction indicating subroutine. Where the computer, scanning servos, and VET are checked for proper functioning. The servos will be positioned 45 degrees in both pitch and roll and the output displayed to the astronaut. A malfunction light will be energized if the position is out of tolerance.

The VET will be set to 0-0 and is observed visually by the astronaut to check proper operation. Proper computer operation is maintained by Go-No-Go test routines as well as initial diagnostic checks.

4.2.4.1.6 Function Selections — The function selector gives the astronaut ability to select the following functions:

- Ephemeris - where fixes are taken and the vehicle's positions and velocities are improved to enable automatic pointing.
- Align and calibrate - where the PTS is pointed to preselected stars to check alignment and focus.
- Ground target - where the astronaut can select certain scans to help him find a target of opportunity. Once the target is found, the system can track it automatically as well as determine its latitude and longitude.
- Space targets - where the system tracks a space target after fixes are obtained.

4.2.4.2 Ephemeris Mode (Assigned Ground Target) (I-2, 3, 4)

4.2.4.2.1 Filtering Procedure — At times t_o, estimates of vehicle position and velocity, together with a covariance matrix of estimates of position and velocity uncertainties, are accepted from the ground. Vehicle equations of motion containing oblateness and drag terms are then integrated in earth-centered inertial coordinates until observations on the known ground target are to begin.

Simultaneously, the inertial coordinates of the targets are updated together with the covariance matrix of position and velocity uncertainties. PTS pointing angles are then computed, which would, if the position of vehicle and target together with the orientation of the vehicle with respect to inertial space were known exactly, point the PTS along the LOS from the vehicle to the target. Because of discrepancies between true and computed vehicle attitudes and position, the actual roll and pitch angles required to point the scope along the LOS from vehicle to target differ from the precomputed ones. Assuming that the vehicle attitude is accurately known in inertial space from a star tracker, and the ground target is accurately surveyed, the major discrepancies between the observed and computed pointing angles at a given time instant are due to differences between computed and true vehicle positions and velocities. Under these

assumptions, a Kalman filtering procedure is depicted in the math flow charts to compute the position and velocity of the satellite.

4.2.4.2.2 Pointing Angle and Fix Taking — Scope pointing commands are determined by finding the relative position coordinates in the inertial frame and transforming them to the vehicle frame. The transformation matrix will be updated using precise attitude derived from the star trackers.

Fixes are taken after the operator has positioned the crosshairs on the target and presses the fix button. To position the crosshairs, a rate signal from the hand control is routed through a proportional plus rate control. This signal is then added to the computed gimbal angles and sent to the I/O and scanning servos.

4.2.4.2.3 Time-to-Go and Sun Angle Computations — Time-to-go can be defined as the elapsed time for the vehicle to move from its existing position to a position enabling the PTS operating within a 0 ±60-degree cone to just see the target. To accomplish this task, the cross-product of the vehicle position and velocity vector must be taken to find the vehicle orbit plane normals, n_x, n_y, and n_z.

Using these and the constraint that the target orbit plane is bounded by the vehicle position vector, the two points of intersection with the target plane can be found by the solution of the quadratic equation. Simple logic is used to select the correct intersection point, after which the computation of the central angle and the time to go follows directly.

The tracking time calculation is of a similar nature and is also based on the distance from the target to orbital plane.

The sun angle conputation determines the angles ϕ and θ to point to the sun. When the actual gimbal angles are both less than 20 degrees from the sun angles, the sun shade is dropped. This system is also augmented by sun sensors mounted on the scanner pitch gimbals.

4.2.4.2.4 Ground Target — Detailed investigations have not been made of the ground target or target of opportunity functions, but, equations for a tentative treatment of the target of opportunity mode are given in Section I-4 of the block diagram. The procedure employed regards the position and velocity of the satellite to be known, as well as the radius of the earth and the earth's angular velocity of rotation. The procedure utilizes measurements of the direction of the satellite earth target LOS to estimate the earth target position and velocity.

4.2.4.3 Space Targets (I-5)

The determination of the position and velocity of a space target by observations of the LOS from the satellite to the target is in principle soluble by a Wiener-Kalman filtering procedure. This procedure is analagous to that employed for determining the position and velocity of a satellite from observations of the LOS from the satellite to a known ground target. Since both the position and velocity of the space target and the position and velocity of the satellite might not be known exactly, a straightforward application of the filtering procedure would involve the estimation of 12 state variables and the position and velocity of this target and tracking vehicle.

In attempts to implement such a procedure, difficulties will probably arise in conditioning the filter equations. Also, a major portion of the study of any proposed filtering procedure will be the determination of a judicious choice of state variables.

4.2.4.4 Auto Scan Mode (I-6)

There are four automatic scan modes selectable by positioning the scan select switch:

- Raster about preselected target
- Raster about ground track
- Raster about target of opportunity
- Spiral scan about best estimate of target location.

The auto scan mode has been thoroughly studied and is discussed in (Section 3.5).

4.2.5 IVSS Primary Digital Math Flow Description Utilizing Hand Control Rate Prediction Techniques

The description for this system is identical to that given for the extended capability digital math flow, with the following three exceptions:

- There is no updating of the ephemeris.
- LOS rates are computed using measured body axis rates and measured gimbal axis rates.
- Initial pointing angles are computed based on using a horizon sensor and a drift sight to align the vehicle x axis along the relative velocity vector.

The math flow for this system is shown in Figure 4-9.

4.3 Optical Systems

4.3.1 MOD 1

The conceptual optical configuration of the PTS, based on the requirements stated in the IVSS RFP is shown in Figure 4-10.

The PTS was to be a periscopic optical sighting system with moderate magnifications coupled to the inertial platform/computer complex to allow

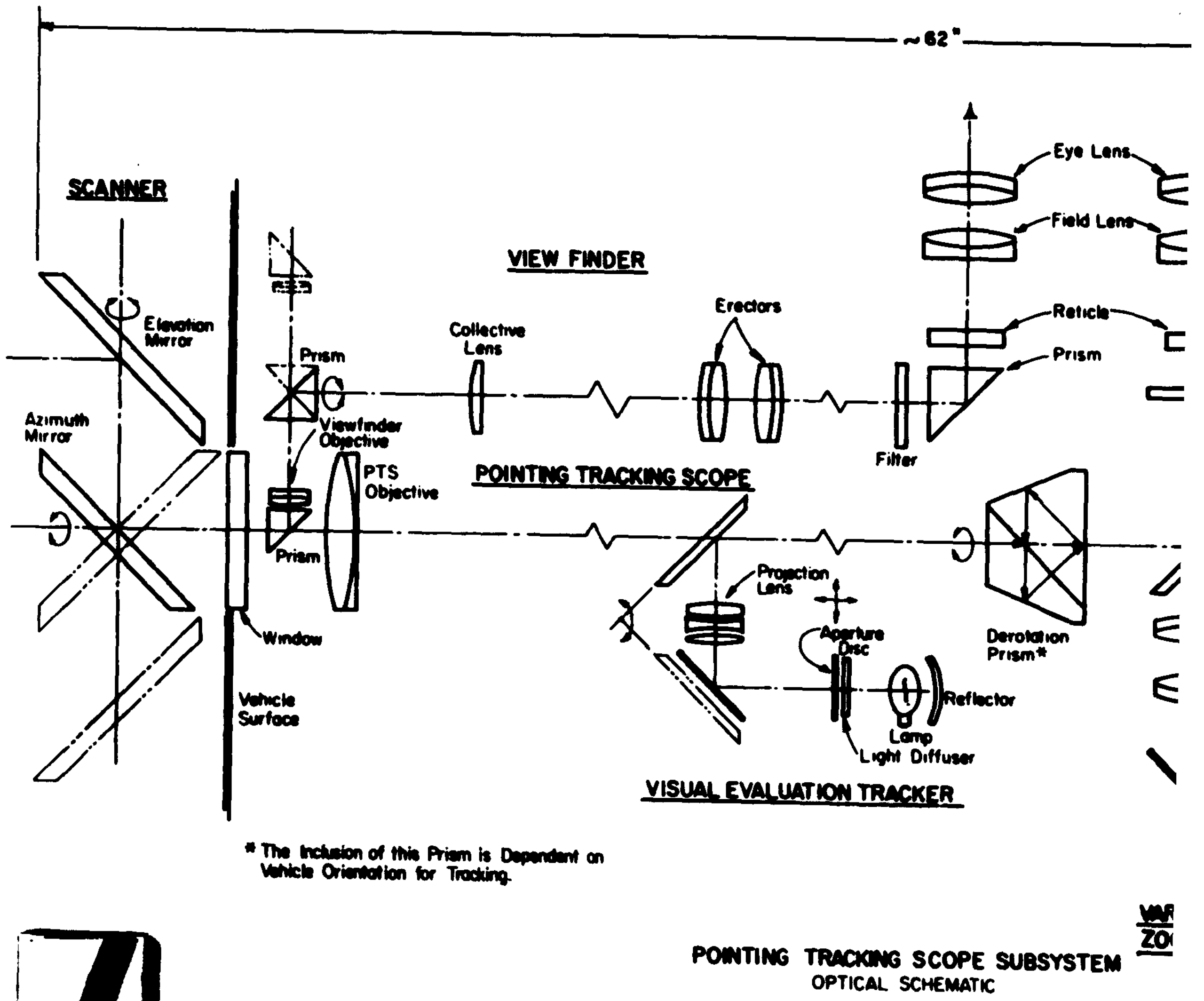


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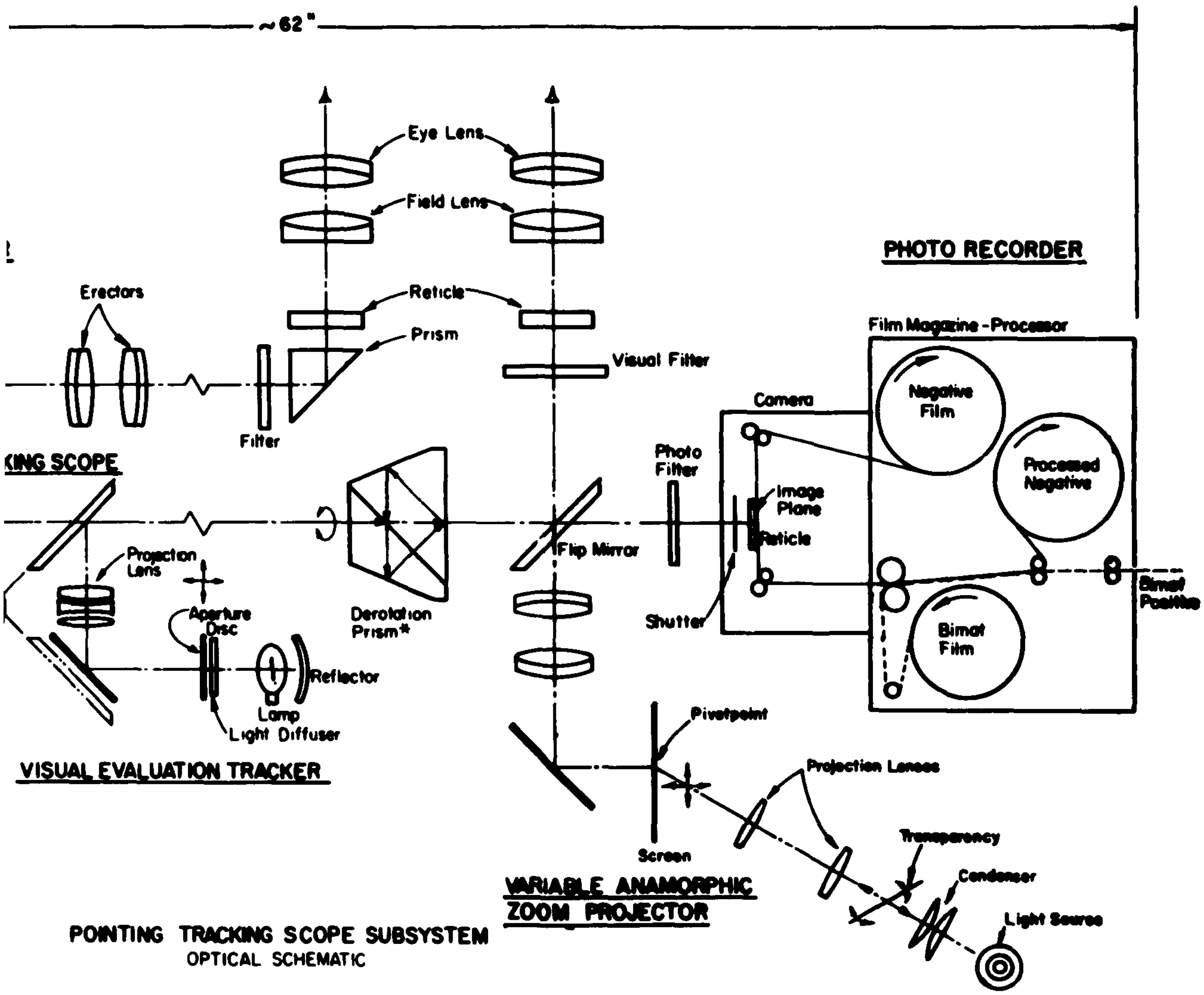
Figure 4-10. Pointing Tracking Scope-Optical Schematic (MOD 1)



POINTING TRACKING SCOPE SUBSYSTEM
OPTICAL SCHEMATIC

2

LOS observations of terrestrial landmarks. The PTS was designed to accomplish seven tasks: (1)viewfinding; (2) pointing; (3) tracking; (4) photo recording; (5) critical visual observations; (6) operator visual evaluation; and (7) operator briefing. The system consisted of six units: (1) scanner; (2) veiwfinder; (3) pointing-tracking scope; (4) photo recorder; (5) visual evaluation tracker; and (6) variable anamorphic zoom projector. The last two features are desirable, but not essential to the experiment.

As conceived, the PTS is a stationary refractive system having a variable magnification capability and utilizing gimballed mirrors for scanning, pointing, and tracking. The optical system configuration compatible with the provision of capabilities, both for its utilization in a scanning or acquisition mode and in a tracking mode. A coupled camera, optically linked to the PTS, allows recording of targets as seen by the astronauts through the PTS. The reticle pattern is superimposed on the image.

4.3.1.1 Scanner
A primary optical consideration is the selection of the scanning element. The requirement is to choose the least complex, lightest, and most compact unit best suited to the environmental demands. One objective of the design is to provide hemispherical scanning coverage. In addition, the photovisual requirement for a 4.8-inch was considered. The logical scanning element is a two-mirror altazimuth (pitch-roll) scanner. One mirror provided the azimuth scan and the other the altitude scan. The mirrors are first-surface mirrors of lightweight, fused quartz construction. They will be elliptical in shape and about 5.0 by 7.0 inches.

4.3.1.2 Viewfinder
The basic requirements for the photo-visual optical system are:

- The field of view must be wide enough to pick up the target.
- The relative aperture must be high enough to see and record the image under the prevailing lighting and atmosphere conditions.
- The physical aperture must be large enough so that the Razleigh limit does not apply to the detail desired.
- The focal length must be long enough to have sufficient detail appear in the final image.

Since the wide field requirement was alien to the other specifications, separate instrumentation in the form of a viewfinder is provided. The function of the viewfinder is to acquire the object and center it on the crosslines so that it is within the much narrower field angle of the PTS.

4.3.1.4 Photo Recorder

The recording camera for the PTS is a 35-mm, single frame sequence camera. Shutter speeds from 1.000 to 0.002 second are to be provided. A filter turret with suitable photographic haze filters will be located ahead of the film plane.

The film magazine-processor section contains a negative film supply, processing film supply, and the processed negative take-up reel. There are several "dry" film development processes applicable to the space environment. One is the Kodak Bimat system, which uses a processing film to develop the exposed film to a negative. At the same time the processing Bimat film becomes a positive. The Bimat processing time for the recommended film was 2 minutes at 90 to 100°F.

4.3.1.5 Visual Evaluation Tracker

To periodically evaluate the observer's visual tracking capability, a visual evaluation tracker will be built into the PTS. It provides a moving target programmed by the computer for the observer to track.

The VET measures the tracking performance of astronauts both on the ground and in space. The baseline data collected on the ground prior to the orbital mission will be compared with the data collected during the space flight from the VET to detect changes in skills.

4.3.1.6 Variable Anamorphic Zoom Projector

Briefing material consisting of printed instructions, drawings, and photographs on a film strip will be presented to the astronaut through either eyepiece. The variable anamorphic zoom projector is used for the briefing display. It forms an image on a rear-projection screen for eyepiece viewing using both a varying perspective and a compensating magnification correction for slant range change. The view presented exactly matches that seen through the VF or PTS at the present slant range and oblique viewing angle.

The component parts of the projection are the light source, condenser, film strip, projection lenses, screen, and relay lenses.

4.3.1.7 Physical Characteristics of MOD 1 Optical System

Length:	6 inches outside vehicle
	58 inches inside vehicle
Volume:	1.0 cubic foot outside vehicle
	4.0 cubic feet inside vehicle
Weight:	150 pounds

4.3.2 MOD 2

The MOD 2 design was made before getting the results of the system and image quality analysis, human factor studies, and simulation experiments. The MOD 2 system, as portrayed in Figure 4-11, was rather complex due to its many functions, which were:

- Variable power from unity to approximately 100X magnification with a single eyepiece
- Wide-field photographic recording
- High magnification with high-resolution recording photographically
- Reticle pattern overlay on the visual image.

4.3.2.1 Fixed Parameters

This system had certain fixed parameters, and these formed the basis of the design concept. The most important was the 70-mm camera, which employed a lens system of high resolution and known characteristics. Such a lens was the 24-inch Petzval f/3.5.

Another important parameter was a unity magnification visual system with a 40-degree instantaneous full field. Unity magnification was taken as 1.5X which simulated naked eye vision. The focal length of an objective lens for unity magnification must be short to be paired with an eyepiece of reasonable dimensions and suitable eye relief. A wide field objective of 2-inch focal length (F) was readily available and could be used with an eyepiece of 1.33-inch F.

4.3.2.2 Basic System

The basic system had (1) a short-focus, wide-field objective for the low-power visual system, and (2) a 24-inch F objective, which could also be used for a high-magnification visual telescope as well as for the camera. With a common eyepiece the magnifications were 1.5X and 18X, leaving too wide a gap between acquisition and tracking and not enough high magnification for accurate tracking of small objects. A power changer was suggested, and one of the least complicated was the variable-power eyepiece erector system of two moveable lenses. This was a fairly simple design which could change system magnification by factors of 2 and 3, extending the magnification range to 1.5, 3, 4.5, 18, 36, and 54X. It does not have the complexity of a zoom system.

The next consideration was to combine the two systems at a convenient plane with a retractable mirror that allowed switching from one to the other and that relayed the primary objective images to the eyepiece location. This involved a multi-lens path consisting of field lenses, relay lenses, and mirrors. The relay lenses simply transfer the primary

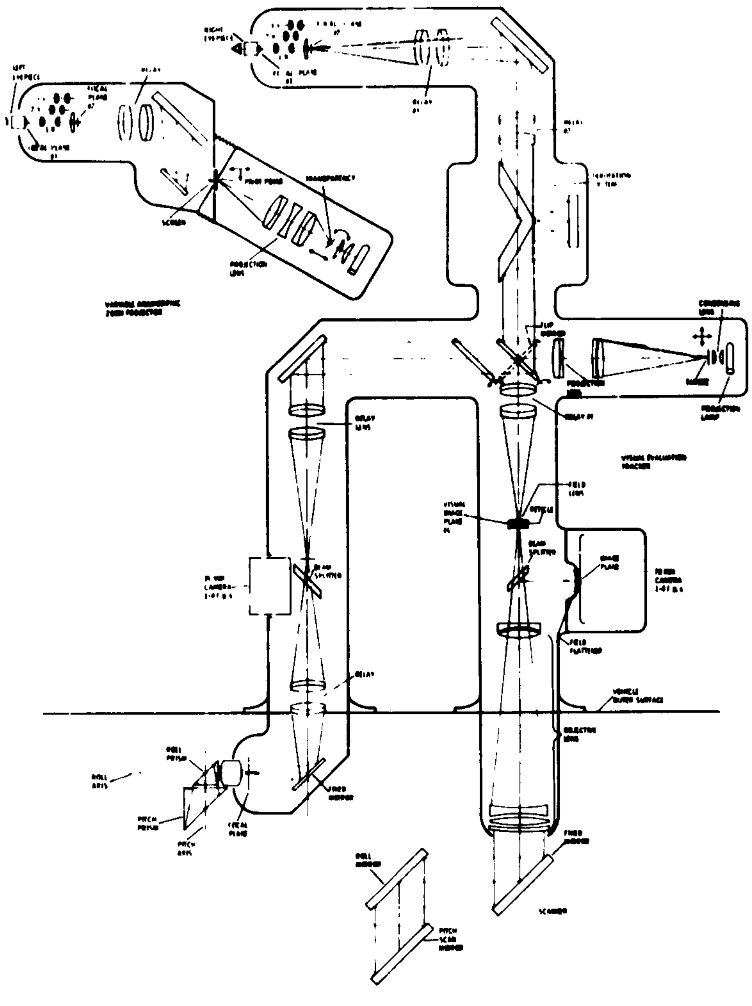


Figure 4-11. Pointing-Tracking Scope - Optical Schematic (MOD 2)

image plane along the optical path, and they must have the same or higher numerical aperture than the objective. The longer the focal length, the fewer the number of lenses but the larger the diameter. A compromise must be made between size and quantity of lenses. The field lenses are located at or very close to focal planes, and have the sole purpose of restricting the system diameter by imaging the system's entrance pupil or successive relay lens pupils. They are relatively simple in design, because they introduce no lens power and practically no aberrations.

Relay lens systems are commonly designed as pairs of telescope objectives facing each other, with a collimated ray path between. Some off-axis vignetting is caused by this arrangement, but this disadvantage is offset by the advantage of a smaller tube diameter and path lengths for the introduction of auxiliary systems and derotation prisms or mirrors.

The photographic lens was the 24-inch f/3.5 Itek Petzval, with a beam splitter at 45 degrees between the second element and the field flattener. The image would have a maximum dimension of 2.10 inches.

Rays undeviated through the beam splitter would form the second image of the system on focal plane No. 1. There would be a slight degradation in resolution due to the tilted plane parallel plate, but the image should still be better than that of the photographic film.

Following image No. 1 is a field lens, serving only to image the entrance pupil of the objective on the second pupil at relay lens No. 1. The latter lens collimates the divergent rays.

Between relay No. 1 and a turret carrying relay No. 2 and relay No. 3, rays are parallel from any point on image plane No. 1. Relay No. 3 gives a 1:1 magnification, and No. 2 gives a 1:2 magnification.

The optical path length between relays serves the following purposes:

- Fills in the space between the objective and the eye position selected
- Allows for over-all length adjustments
- Provides for the introduction of the low-power branch of the system
- Provides space for the derotation device.

Following the relay system was the focal plane No. 2 and a field lens. A pair of doublets relays the image at 1:1 to the eyepiece focal plane, when in the position shown. When a knurled ring actuating linear motions of the lenses, each at a different rate, was turned, the combination of lenses varied in equivalent focal length and in the nodal plane positions. Magnification from focal plane No. 2 to No. 3 varied continuously from 1:1 to 1:3, without changing focal plane positions.

The focal plane No. 3 was located at the field stop of the eyepiece that was capbable of including an apparent field of 60 degrees.

4.3.2.3 Low-Power System

The low-power objective would have its own scanning system synchronized with that of the photographic high-power visual. Its focal length would form a 40-degree image identical in size to that of the 60-degree image viewed in tne eyepiece. The image would be relayed at 1:1 and introduced into the primary system with a retractable 45-degree mirror in the collimated beam sections. At the eye end of the system it would also utilize the power changer for different magnifications.

The low power objective would form an image which when relayed at 1:1 would have a magnification of 1.5X Relay lenses No. 2 and 3, mounted on a turret, allow a choice of 1.5 or 3X. The eyepiece power changer gives an additional choice, extending the magnification range from 1.5 to 9X.

The high-power telescope system would also have a 6:1 range in magnification, starting with approximately 25X and going as high as 150X.

4.3.2.4 Scanners

Both scanners are of the roll-pitch type, so that once a target is on the crossline the pitch servos will do the entire scan with only slight adjustments by the roll servos. For large field angles (25 degrees or more), prisms are more compact and weigh less than mirrors.

4.3.2.5 Recording

The system would have two modes of operation, a high-magnification mode for fine acquisition and tracking, and a low-magnification mode for coarse acquisition and tracking. It was suggested that each mode have a recording-sampling camera, since the likelihood of a single optical system for both modes was remote.

Assuming that the total system would have low-and high-magnification, both should be equipped with sampling cameras in the event that major movements occur. It was also assumed that the majority of trials would be made using the high-magnification system for tracking after acquisition, rough tracking would be accomplished with the low-magnification system. A continuous record of both would greatly aid in reducing the information during analysis.

In general, the optimum position for the sampling cameras is in the focal plane of the primary optics for each mode. This location would assure a minimum degradation of the high-resolution image produced by the primary optics.

It was assumed that the low-magnification mode primary optics would have a 50-mm focal length and a 40-degree field of view. The high-magnification mode primary optics would have a 24-inch focal length and a 5-degree field angle. The formats would be 35-mm and 70-mm, respectively, to best utilize existing camera systems.

4.3.3 MOD 3

The major difference between the optical configuration of MOD 3 and that of MOD 2 is the continuous visual observation at unity magnification by a second observer. This was suggested at the 5 October technical progress meeting. The MOD 3 optical schematic is shown in Figure 4-12.

4.3.4 MOD 4 (Recommended Design)

MOD 4 of the optical configuration reflects the results of the system and image quality analysis, human factor studies, simulation experiments, and contractor guidance as summarized in Table 4-1. The optical schematic recommended system is shown in Figure 4-13.

The major considerations for selecting this system were the physical constraints, which are:

- 6 feet maximum in direction of vehicle axis (length)
- 3 feet radially (height)
- 1 foot perpendicular to axis (width)
- 1 foot protrusion outside vehicle.

By placing the bulk of optics outside the vehicle in the form of a fin, it is possible to keep within the constraints. Not included within the physical constraints but considered as accessories are the auxiliary eyepiece, the wide-field camera, cine camera, VET, and the Briefing Presentation Unit.

Several different lenses were considered for the high-magnification, narrow-field optics. A careful study was made of the system requirements based on the task definition of P-1, P-3, and P-2. The most difficult task to perform is P-3. At 160 n mi altitude, the studies indicated that the P-3 experiment requires a 12- to 13-inch aperture, 40- to 55-inch focal length lens. The P-1 experiment requires an 8-inch aperture, 36-inch focal length lens or a 7-inch aperture, 24-inch focal length lens. A table of weights and volumes for the PTS as a function of aperture size is given in Table 4-5.

Because the 13-inch aperture makes such a severe impact on the instrumentation it is recommended that an 8-inch aperture, 36-inch focal length

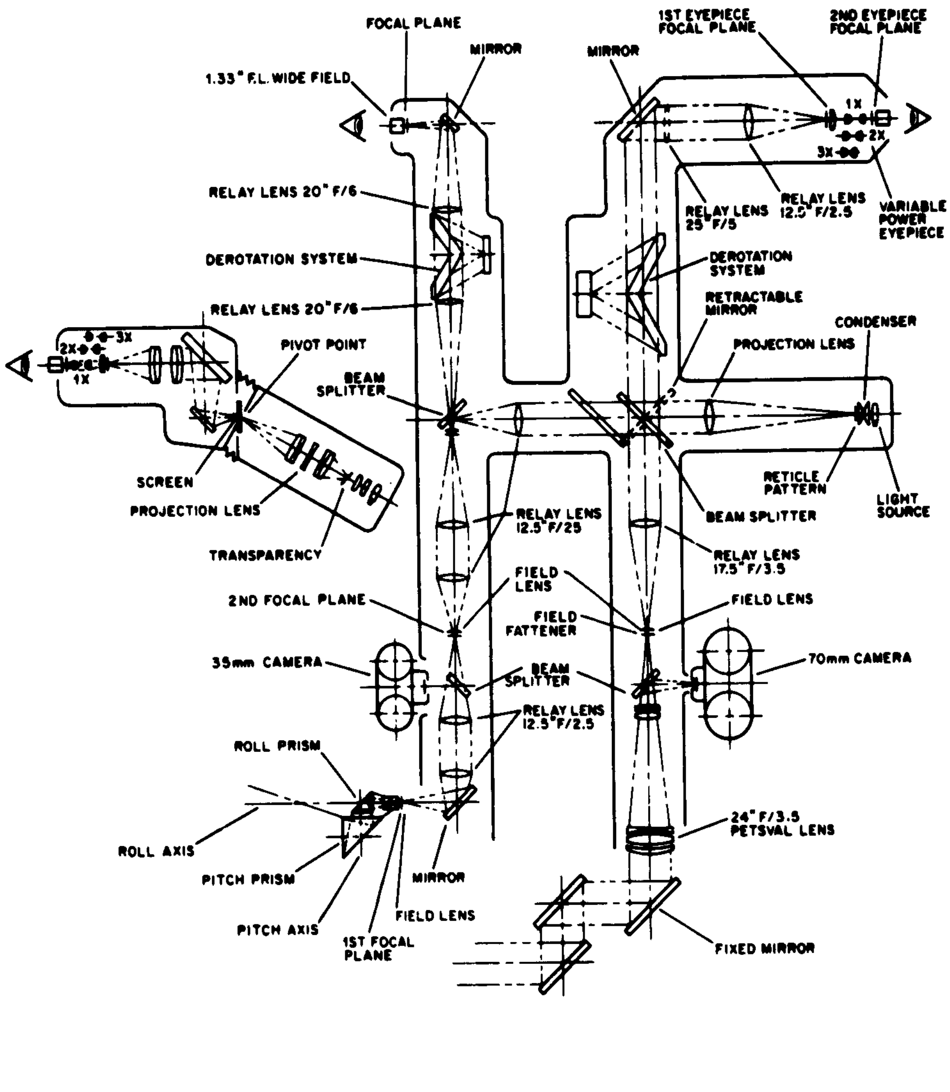


Figure 4-12. Pointing-Tracking Scope - Optical Schematic

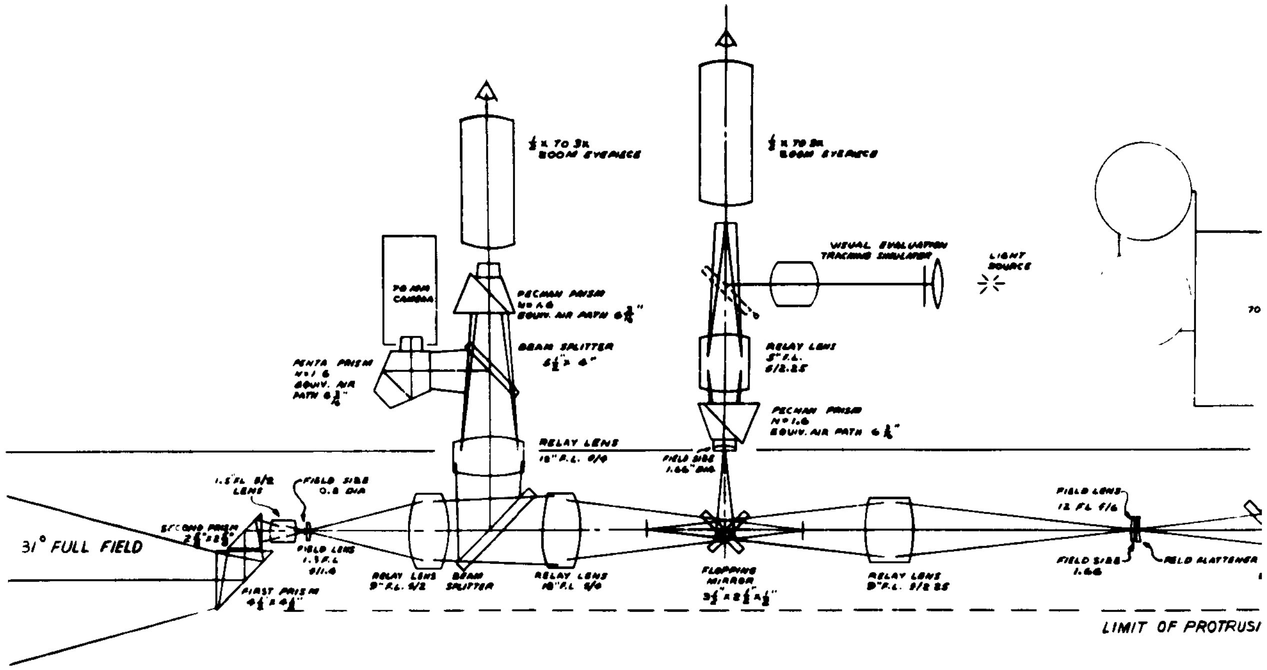
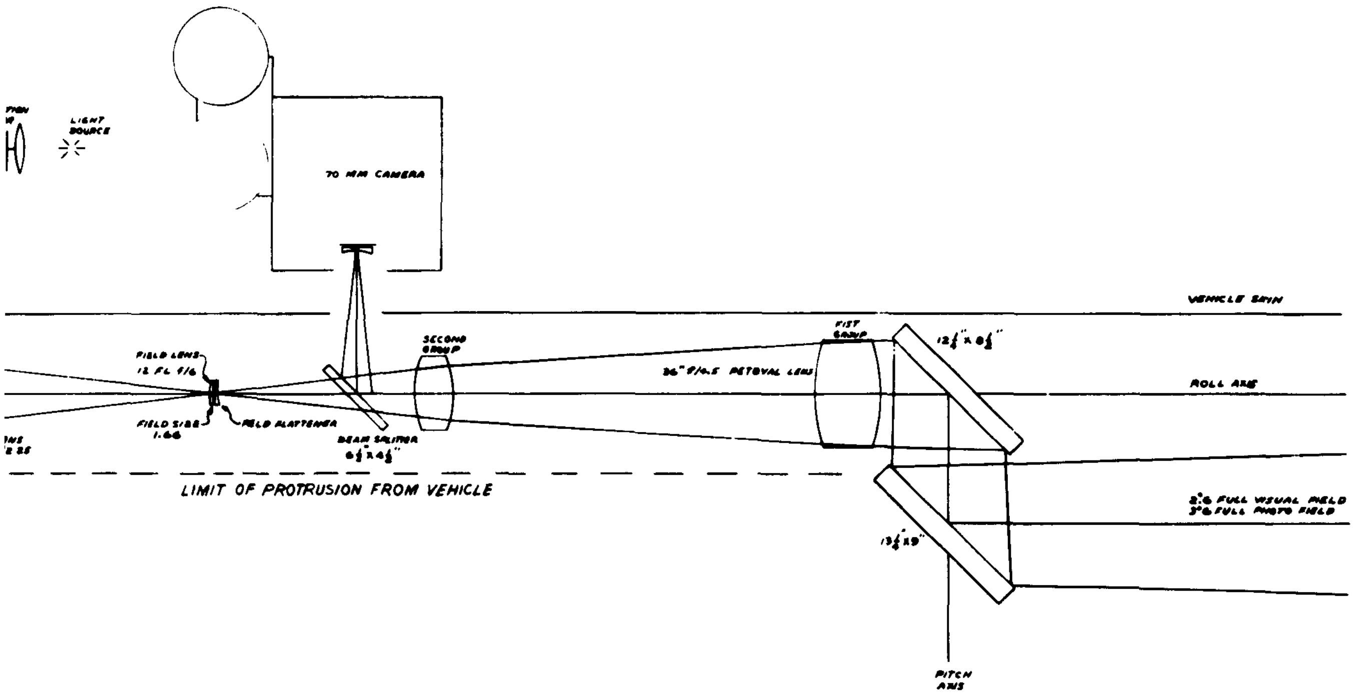


Figure 4-13 Pointing-Tracking Scope Candidate
Optical Configuration Schematic
(MOD 4, Recommended Design)


LIGHT SOURCE
70 MM CAMERA
VEHICLE SKIN
FIELD LENS
12 FL f/6
FIELD SIZE
1.66
FIELD FLATTENER
BEAM SPLITTER
SECOND GROUP
FIST GROUP
36" f/4.5 PETZVAL LENS
ROLL AXIS
LIMIT OF PROTRUSION FROM VEHICLE
2.6 FULL VISUAL FIELD
3.6 FULL PHOTO FIELD
PITCH AXIS

2

Table 4-5

WEIGHT & VOLUME TRADE-OFF VS TELESCOPIC APERTURE DIAMETER

	Weight (pounds)				Volume (cubic feet)			
	Aperture (inches)				Aperture (inches)			
Part	5	7	8	13	5	7	8	13
Telescope Internal	51	51	51	51	10	10	10	10
Telescope External	14	14	14	14	10-3/4	10-3/4	10-3/4	10-3/4
Objective	10	25	50	175	3/4	1-1/4	2-1/4	3-1/4
Scanners Wide Field	20	20	20	20	3/4	3/4	3/4	3/4
Scanners Large Aperture	50	70	85	150	3/4	1	1-1/4	2-1/4
Auxiliary Eyepiece	5	5	5	5	1/4	1/4	1/4	1/4
Base Plate	87	87	87	100	6	6	6	6
TOTAL	237	272	312	515	29.25	30	31.25	33.25

be used. It is also suggested that the P-3 requirements be handled with special, unique instrumentation. The reasoning behind these recommendations is:

- It does not appear possible to design a 13-inch aperture system and keep it within the physical constraints set.
- For the 13-inch aperture, there would be an increase in weight of at least 200 pounds.
- Its installation would be quite difficult, since the outside fin is already 13.3 feet long. The 13-inch system would add at least three feet to the fin.
- Maintaining alignment and focus would be considerably more difficult.
- The effects of motion will be more significant for longer focal lengths.
- Procurement of the larger system in the time allotted may be difficult, especially obtaining the necessary glass.

This recommended design is discussed in detail in Section 5.1.1.

4.4 Tracker Servo Configuration

4.4.1 Digital Servo Candidate

Figure 4-14 is a block diagram of the candidate servo that IBM feels will best meet the pitch servo requirements. This is the same servo described functionally as Model 1a in Section 3.3.

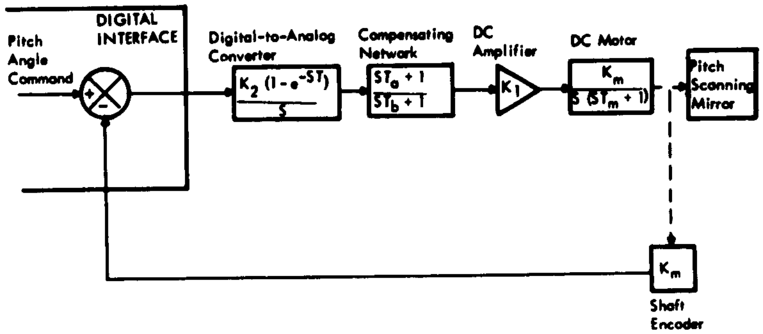


Figure 4-14. Candidate Pitch Tracking Servo-Primary Mode

4.4.1.1 Servo Components

All major components are chosen to attain the higest possible accuracy consistent with the rate and acceleration requirements, and are off-the-shelf items available from at least two sources. The motor is a direct drive d-c torque motor that has the following important advantages over other servo system actuators:

- High torque-to-inertia ratio at the load shaft
- High coupling stiffness
- Fast response
- High resolution
- High accuracy at low speeds
- High linearity
- Compact adaptable design
- High reliability and long life

Other types of acutators had many of these advantages, such as the Harmonic Drive, which claims good accuracy and linearity but was precluded because IVSS system requirements were not met. A-C motors were also precluded because of the relative size necessary for the required torque, inability to drive loads slowly without gearing, and large power consumption while at standstill.

Table 4-6 shows the large variety of commercially available d-c motors. The Inland, Magnetic Technology, and Kearfott motors are d-c torquers,

Table 4-6

CHARACTERISTICS OF SOME AVAILABLE D-C MOTORS

Manufacturer	Type	Peak Torque (lb/ft)	Peak Power (watts)	Weight (lb)	Volume (in^3)
Magnetic Technology	1500C-038	0.0468	70	0.1	0.66
	1937-050	0.114	57	0.263	1.47
	2813-063	0.2344	36	0.625	3.88
	2813-133	0.677	56	1.56	8.23
	3730-134	1.56	140	2.06	14.4
	5125-160	3.65	135	5.19	33.0
Inland	T-0709	0.0344	52	0.112	0.55
	T-1352	0.104	60	0.312	1.46
	T-2171	0.625	50	1.56	9.3
	T-4036	1.8	91	3.0	25.7
	T-5135	4.0	119	8.5	47.9
	T-7203	22.0	581	22.0	163
	T-10035	100.0	1046	110.0	738
	T-18002	900.0	1450	335.0	3165
	T-36001	3000.0	7350	1200.0	16300
Kearfott	Size 20	0.104	55	0.312	1.72
	Size 38	1.0	55	1.5	11.9
	Size 52	1.8	112	3.0	25.7
Printed Motors	368	0.78	60	3	24.1
	488	1.95	144	6.5	50.6
	668	6.12	288	13	100.0
	1028	43.75	750	57	448
Aeroflex	TQ2	0.0156	±25	degree range	
	TQ5	0.52	±60	degree range	
	TQ6	1.25	±10	degree range	
	TQ1	2.08	±8	degree range	
	TQ8	10.0	±17	degree range	
	TQ9	75.0	±14	degree range	

the Printed Motor device contains a disk-shaped armature containing no iron and which is produced by printed circuit techniques, and the Aeroflex device is a d-c torque motor that has no brushes or commutator but is limited in rotation. The Inland T-4036 torquer provides sufficient torque to drive the pitch scanning mirror with minimum power, weight, and volume penalties; its parameters used in calculating Table 3-11.

Standard d-c torque motors can also be used as low-speed, directly driven tachometer generators. Torquers considered for this application have a wound armature and a permanent-magnet field, so no separate electrical excitation is necessary. Table 4-7 shows representative physical tradeoffs involved in obtaining a small ripple voltage, which is essential to meet the IVSS accuracy requirements. This ripple voltage is essentially proportional to the average voltage value and is dependent upon many design factors. Reference to the table shows that the lowest ripple voltage is 0.2

Table 4-7

CHARACTERISTICS OF SOME AVAILABLE D-C TACHOMETERS

Manufacturer	Type	Maximum Ripple Voltage %Deviation from Avg.	Weight (lb)	Volume (in^3)	Ripple Cycles per Rev.	Max. Sensitivity volts per (rad per sec)
Inland	T-1321	7	0.32	1.47	31	0.2
	T-4006	4	3.0	25.7	56	11.0
	T-7202	1	11.5	103	97	54.0
	TG-10001	0.2	40.0	446	297	48.0

percent using TG-10001, so the highest accuracy attainable if this tachometer were used would be only slightly better than 0.2 percent, which is not good enough for the IVSS. The weight and volume penalties also preclude use of tachometers in the pitch servo loop.

The encoder is a single-turn photoelectric device requiring no brushes, gears, or reference rotor. It has a continuous output without the necessity of code conversion. Table 4-8 gives characteristics of some commercially available encoders. The Wayne-George BO-19 meets the IVSS accuracy requirements, and its parameters were used in calculating Table 3-11. This 2^{19}-bit optical shaft angle encoder is mounted directly to the pitch shaft and is the feedback element that supplies the digital interface with highly accurate pitch shaft angle position.

The amplifier provides the necessary signal and power gain to drive the motor, and the compensating network is included to insure stability and gain at the frequencies of interest. The digital-to-analog converter is an IBM-developed device that changes signal information from digital form to its analog equivalent, K2 being the scale factor of the converter output.

4.4.1.2 Analysis and Results

Sampling Rate — The maximum velocity requirements for tracking terrestial targets of 2.5 degrees/sec (9,000 arc sec/sec) are used to determine the sampling rate of the closed loop. Since the resolution of the shaft encoder is 2.47 arc sec, the minimum sampling rate is:

$$\frac{9000 \text{ sec/sec}}{2.47 \text{ sec}} = 3644 \text{ samples/sec}$$

Table 4-8

CHARACTERISTICS OF SOME AVAILABLE ENCODERS

Manufacturer	Type	Angular Quantum (arc/sec)	1 Accuracy (arc/sec)	Power Req'd (watts)	Weight (lb)	Volume (in^3)
Wayne-George	BD-18	4.94	2.25	30		
Optical Unit					4.5	40
Translator					7	340
Wayne-George	BD-19	2.47	1.10	30		
Optical Unit					4.5	40
Translator					8.2	410
Wayne-George	BD-20	1.24	0.56	30		
Optical Unit					14	200
Translator					8.2	410
Microgon		2.48	±1 count (RMS)	150	70	3250
Transducer	512/219					
Electronics	SE-12					
Microgon		1.24	±1 count (RMS)	235	70	3250
Transducer	1024/220					
Electronics	SE-12A					
Microgon		0.618	±1 count (RMS)	235	70	3250
Transducer	2048/221					
Electronics	SE-12B					

To ensure that the information contained in each bit is utilized, the sampling rate must exceed the minimum rate. A sampling rate of 8kc guarantees that each bit will be sampled at least twice.

Resulting Characteristics — The generalized forward-loop transfer function for the candidate servo is:

$$G(S) = \frac{K_1K_2K_m\,(ST_a + 1)\,(1-e^{-ST})}{S(ST_m + 1)\,(ST_b + 1)\,S}$$

Since the sampling rate is high, the system is essentially a continuous system and is analyzed as such. Using the load parameters given in a preceding section, the forward-loop transfer function is:

$$G(S) = \frac{4000(.0625\,S + 1)}{S(8.518\,S + 1)\,(.005\,S + 1)}$$

$\frac{1 - e^{-ST}}{S}$ can be neglected

Figure 4-15 indicates the closed-loop response. From this diagram, it is seen that:

Bandwidth*	60 radians (9.6 cycles per second)
Phase Margin	55 degrees
Peaking	2.4db at 23 radians

*Torque limiting will occur and will reduce the theoretical band limit.

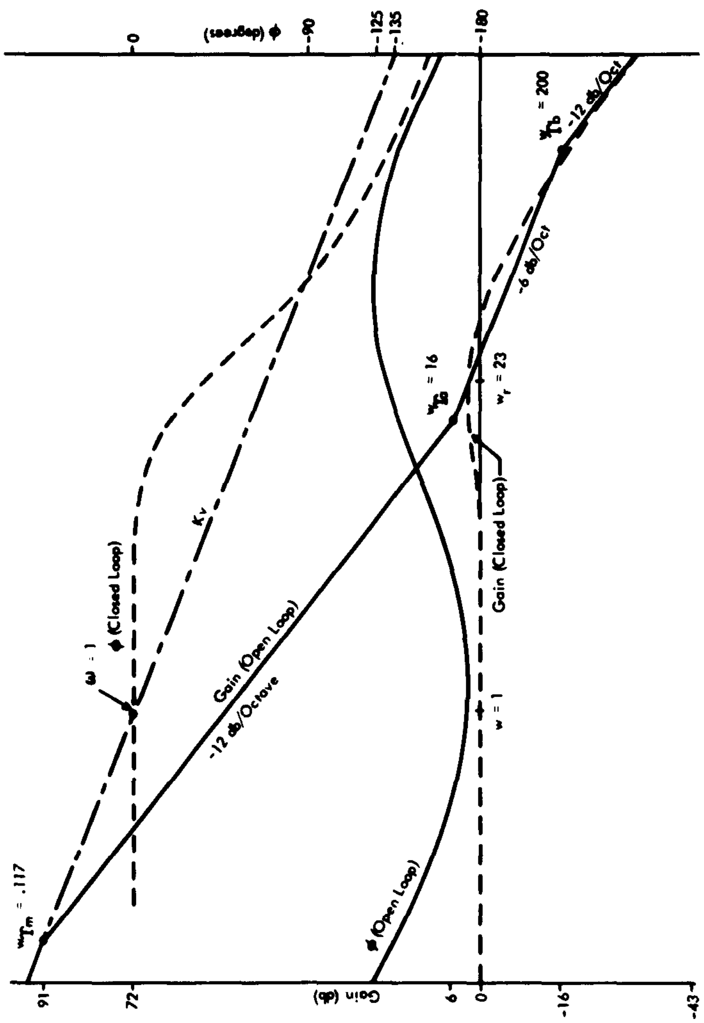


Figure 4-15. Closed Loop Response

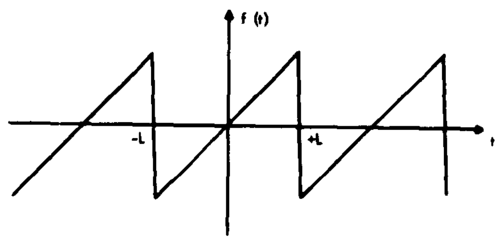
A damping ratio can be obtained as a design parameter by observing that the real root of the denominator of a closed-loop transfer function is larger than the real part of the remaining two roots. The dominating equation is the quadratic:

$$\frac{C(S)}{R(S)} = \frac{93,918\,(.0625\,S+1)}{(S+168.3)\,(S^2+31.7S+557.89)}$$

Another parameter of interest is the steady-state tracking error. For a ramp input, this error is:

$$Ess = \frac{1}{Kv} = \frac{1}{4000} = 0.025\%$$

Computer Noise Effects - The computer noise output can be represented as a ramp voltage, $f(t) = at$, with a period of 2L:



A Fourier analysis of the function yields:

$$f(t) = \sum_{n=1}^{w} \frac{2zL}{n} \sin \frac{n\pi t}{L}$$

For tracking ground objects, the image motion must be smooth to avoid excessive smearing during camera exposure times. The minimum tracking rate is of paramount interest since it will have the smallest gain attenuation. For a velocity of 2520 arc sec/sec (0.7 deg/sec) and a quanta step input of 2.5 arc sec:

Maximum computer output rate = 1kc/sec

a = 2520 arc sec/sec

$$L = \frac{1}{2f} = \frac{1}{2000} = 5 \times 10^{-4} \text{ seconds}$$

and

$$f(t) = 0.8 \sin 628^{0}t$$

for the fundamental frequency. The maximum noise amplitude is 0.8 arc sec and the frequency is 6280 radians per second (1000 cycles per second). From Figure 4-15, the servo system attenuation at this frequency is 43db, so the attenuated noise amplitude is:

$$\text{Noise} = \frac{0.8}{141} = 0.00567 \text{ arc sec}$$

This value is well within the 0.3 arc second amplitude required during camera exposure time, indicating that noise due to quantitizing does not result in erratic image motion.

4.4.2 Analog Servo Candidate

The figure 4-16 illustrates the candidate analog servo. This is the servo described functionally as Model 2 in Section 3.3.

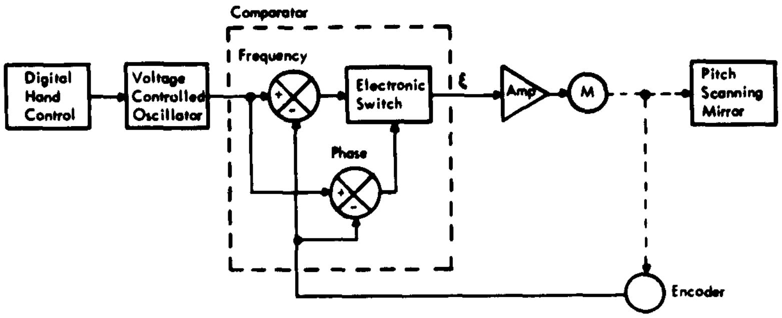


Figure 4-16. Candidate Pitch Scanning Mirror Analog Servo — Back-up Mode

In this configuration, the encoder is used as a precise pulse tachometer, the frequency of its least significant bit output being directly proportional to the motor rate. When the operator tracks an object, the hand-control movements determine the frequency of the voltage-controlled oscillator. This reference frequency is compared to the encoder output frequency, any difference generating a coarse error voltage that controls the motor speed. The frequency range of the encoder output is 1 to 48.2kc (corresponding to pitch velocities of 0.7 to 33.5 degrees per sec), providing a high enough resolution to insure that high accuracy is attained. When the frequency output of the encoder equals that of the oscillator, the coarse error signal becomes negligible and a fine error signal, proportional to the relative phase angle between the two frequencies, becomes significant. This fine error voltage is then used to control the motor speed so that the frequency output of the encoder exactly equals the reference frequency and no relative phase difference exists. These frequency and phase circuits operate simultaneously, the transition from the frequency control mode to the phase control mode being performed automatically and in a continuous manner so no switching signals or transients appear in the error signal.

Absolute speed synchronization is an inherent property of this system, and short-term perturbations of less than one part per million can be

achieved in the presence of drastic variations in supply voltage, torque, and environmental conditions. Since the long-term accumulation of error is zero, a high position accuracy is guaranteed.

The electromechanical components of this system are identical to the ones needed to implement the digital servo candidate. Thus, the analog servo candidate requires only the incorporation of more electronics to provide a back-up mode that will meet the servo requirements listed in Table 3-10. These electronics entail only small penalties in regards to weight, volume, and power (see Table 3-11). Another major advantage of this back-up system is that all other servos receiving pitch angle position (Figure 3-66) will not be affected by a change of system modes.

4.5 Data Management

The data management system (DMS) allows MOL to control and monitor the IVSS experiments. DMS must receive, convert, store, and distribute data concerning targets, vehicle state parameters, operational subsystems, and experiments. It must interpret the data where appropriate, and transfer the data to the communications subsystem for transmittal to the ground.

4.5.1 Definition of the Data Management System

DMS comprises the following major subsystems:

- Data acquisition subsystem (DAS)
- Electronic Interface Units
- Computer
- Recording equipment

DAS collects, converts, and stores data. The data processing subsystem, which consists of two subsystems, the computer and the electronic interface units, performs the mathematical computations and the control functions required for the IVSS.

4.5.2 Data Acquisition Requirements

The DAS primarily will route IVSS data to various MOL equipment. This task comprises four major subtasks: collecting, converting, formatting, and storing all IVSS data which must be subsequently analyzed. The DAS, therefore, interfaces with the console, data adapter, telemetry (and communications), DCS, and IVSS calibration equipment.

As presently conceived, the DAS must place data in at least the four formats listed below. The DAS must also be capable of changing to a different format at any time, especially after a position fix is taken using the camera.

- Normal IVSS data
- Photograph tag data
- Photograph interpretation data
- Alignment/calibration and test data

The "normal" IVSS data that must be collected by the DAS comprises information required to permit ground reconstruction of the particular portion of the experiment being performed. This data gives some indication of astronaut and equipment operation.

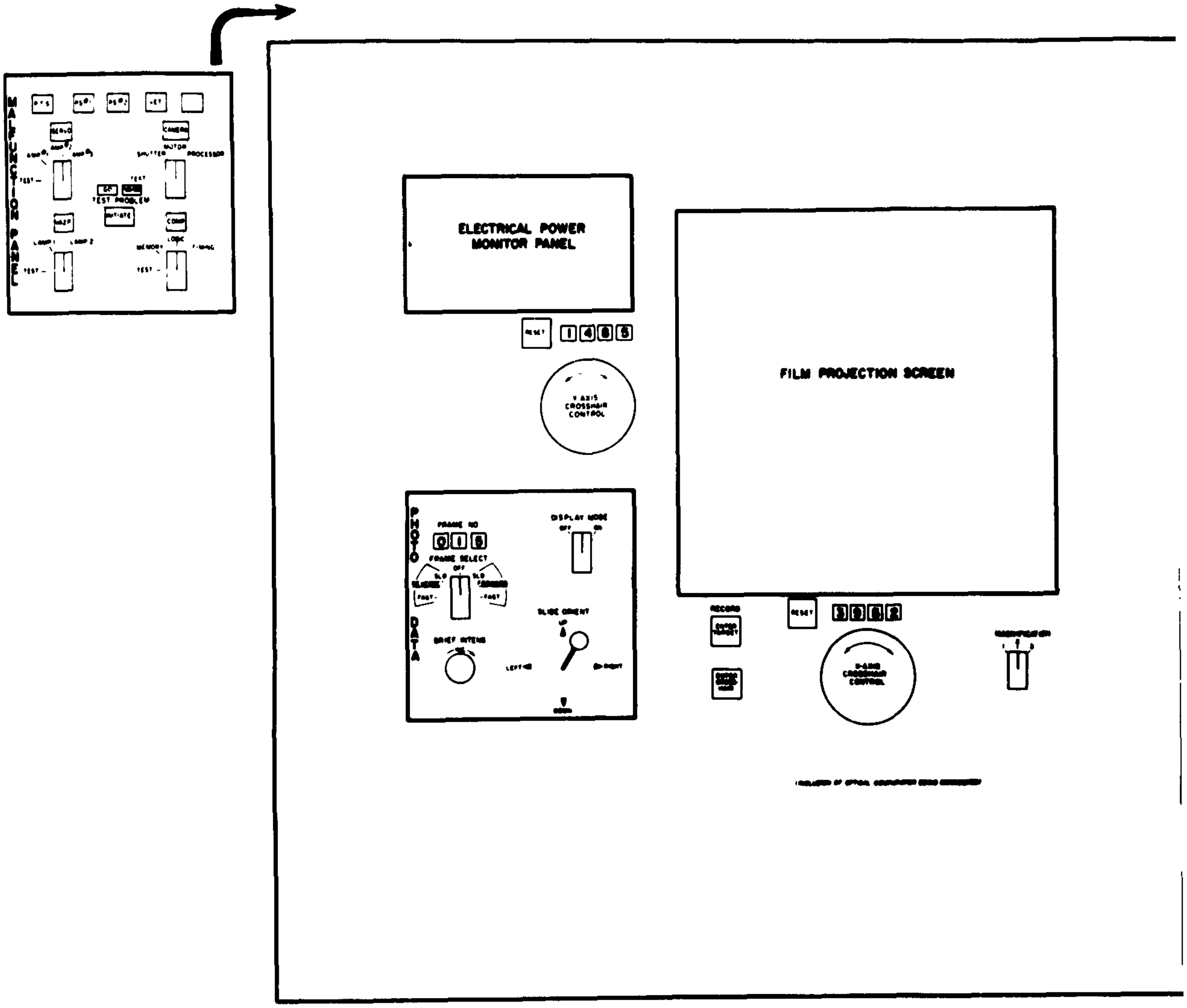
Photograph tag data is required to evaluate astronaut and equipment performance when a photograph is taken. This data, along with data recorded by the astronaut, during photograph interpretation, will permit ground evaluation of astronaut performance in IMC before the hard copy photograph is available. Because of the time-critical nature of the gimbal angles in the PTS and star/tracker, the photographic tag data will be recorded during a computer program interrupt.

To permit evaluation of the IVSS equipment operation, pertinent alignment/calibration data must also be recorded. Although the time required to perform calibration is small, data requirements are large if the PTS servo loop is sampled at the internal sampling rate.

In addition to acquiring and formatting data for the telemetry, the DAS must acquire data from the digital command system for updating computer knowledge of time and vehicle position. DAS must also supply space target ephemeris to the computer on demand. This latter interface is essentially a data-rate assessment, because buffering between the DCS and the computer is hardwired.

4.6 Display and Control Considerations

The synthesis of the displays and controls for IVSS has been directed towards satisfying the functional requirements specified in Section 2. 3. Since the rational of the displays and controls design is strongly affected by human engineering considerations, the discussions pertaining to the console synthesis appears in Section 5. 0 of Volume IV. Figure 4-17 depicts the console layout, which is functional in nature. A detailed discussion of the associated displays and controls is contained in Table 5-1 of Volume IV.



MALFUNCTION PANEL
SERVO
CAMERA
AMP Ø1
AMP Ø2
AMP Ø3
SHUTTER
MOTOR
PROCESSOR
TEST
TEST PROBLEM
COMP
LAMP 1
LAMP 2
MEMORY
LOGIC
ELECTRICAL POWER
MONITOR PANEL
RESET
1 4 8 5
Y AXIS
CROSSHAIR
CONTROL
FILM PROJECTION SCREEN
PHOTO DATA
FRAME NO
0 1 5
FRAME SELECT
OFF
SLO
FAST
DISPLAY MODE
OFF
ON
SLIDE ORIENT
UP
LEFT
RIGHT
DOWN
RECORD
RESET
3 9 8 2
CROSSHAIR
CONTROL

7

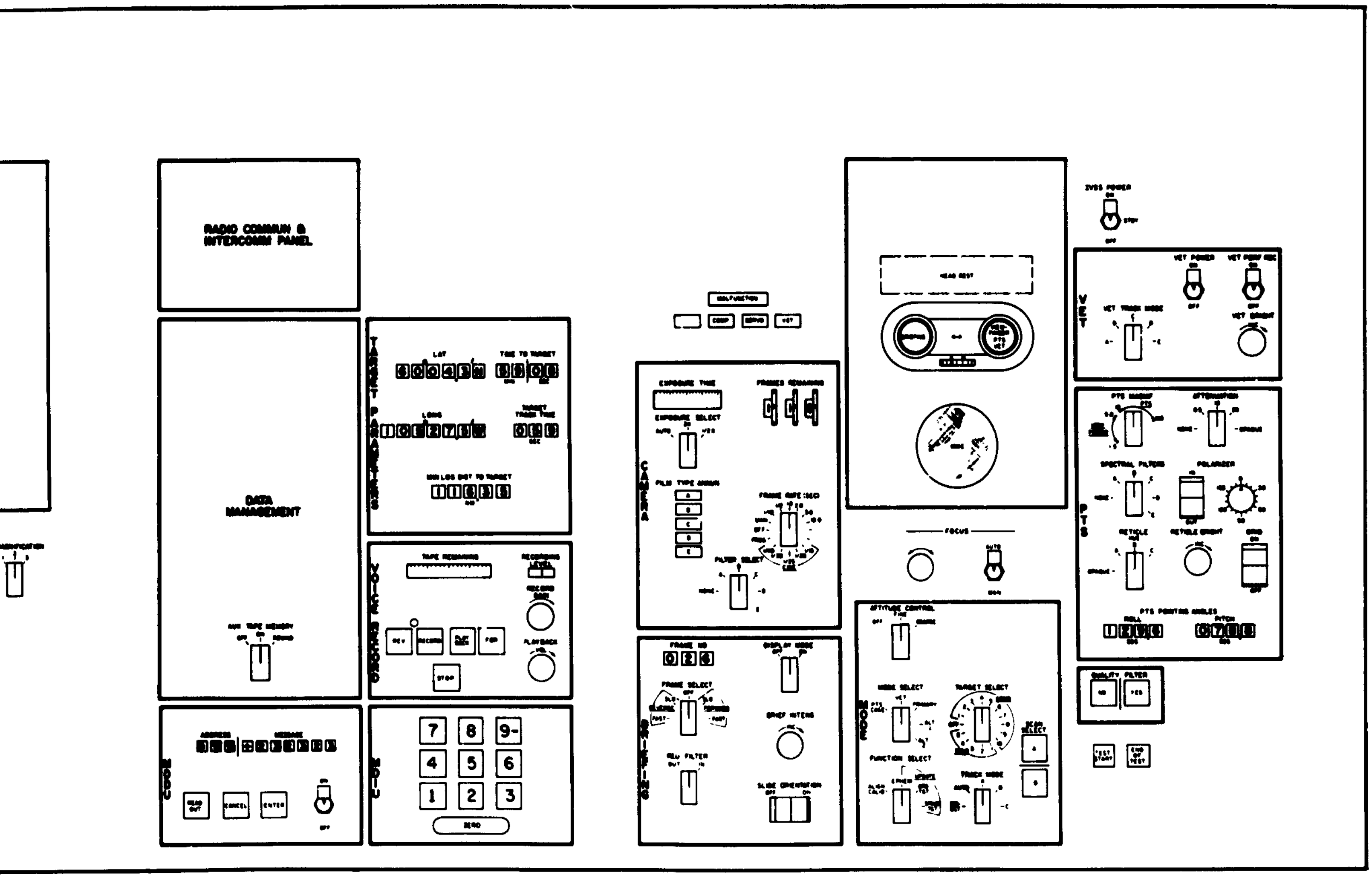


Figure 4-17. Console Layout

5.0 Preliminary Design Recommendations

This section of the report presents the results of Task 7, wherein the IVSS is described and the interface, AGE and ground support requirements are delineated. The cost and schedule items required by Task 7 appear in Volume V. Section 6.6 of this volume contains the Reliability and Maintainability Plans for the phases of the effort described below.

5.1 Description of the Image Velocity Sensor Subsystem

This subsection describes the functional performance and physical characteristics of the IVSS and contains a discussion of critical design problem areas.

5.1.1 The Functional Description of the IVSS

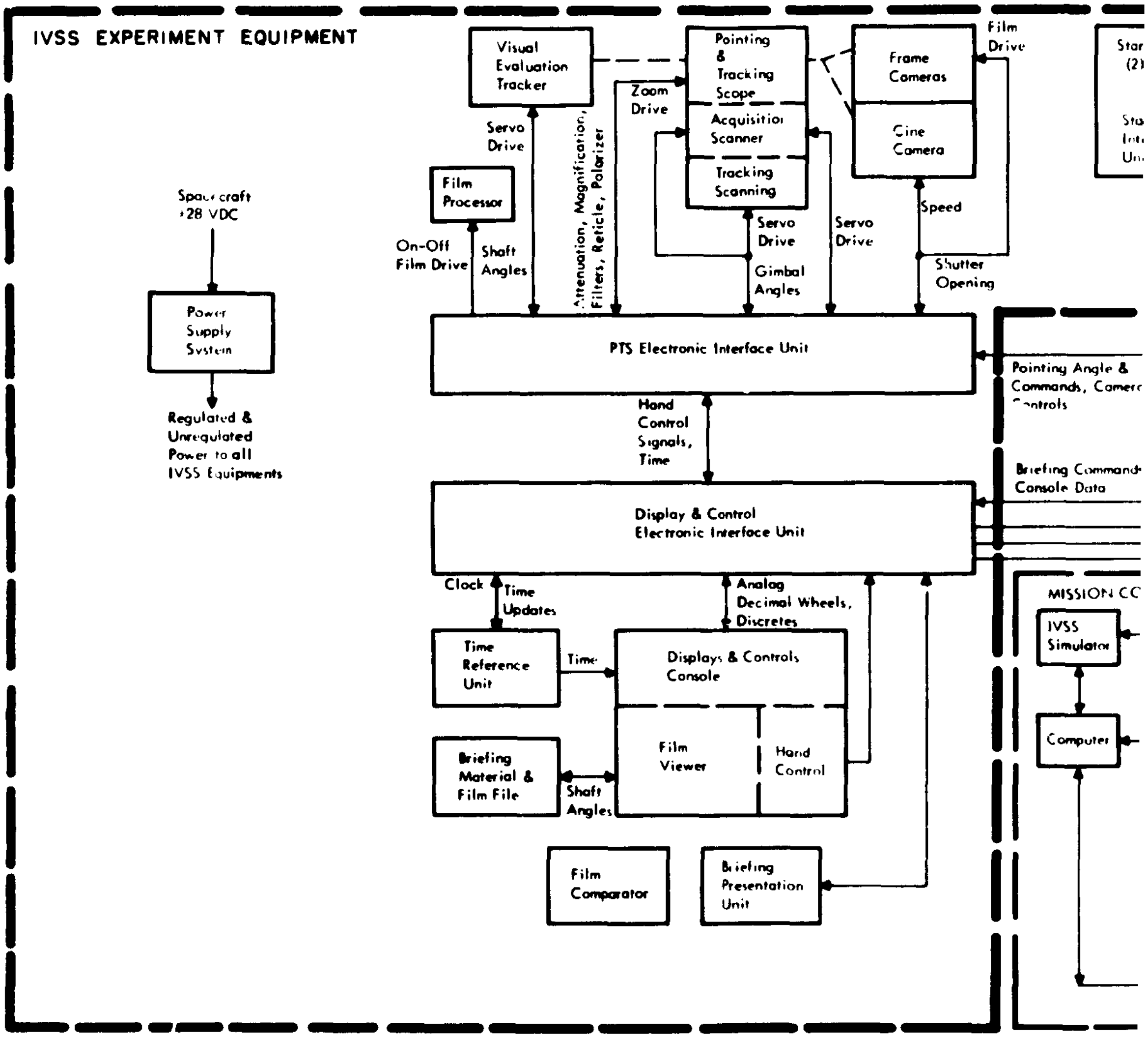
5.1.1.1 Introduction

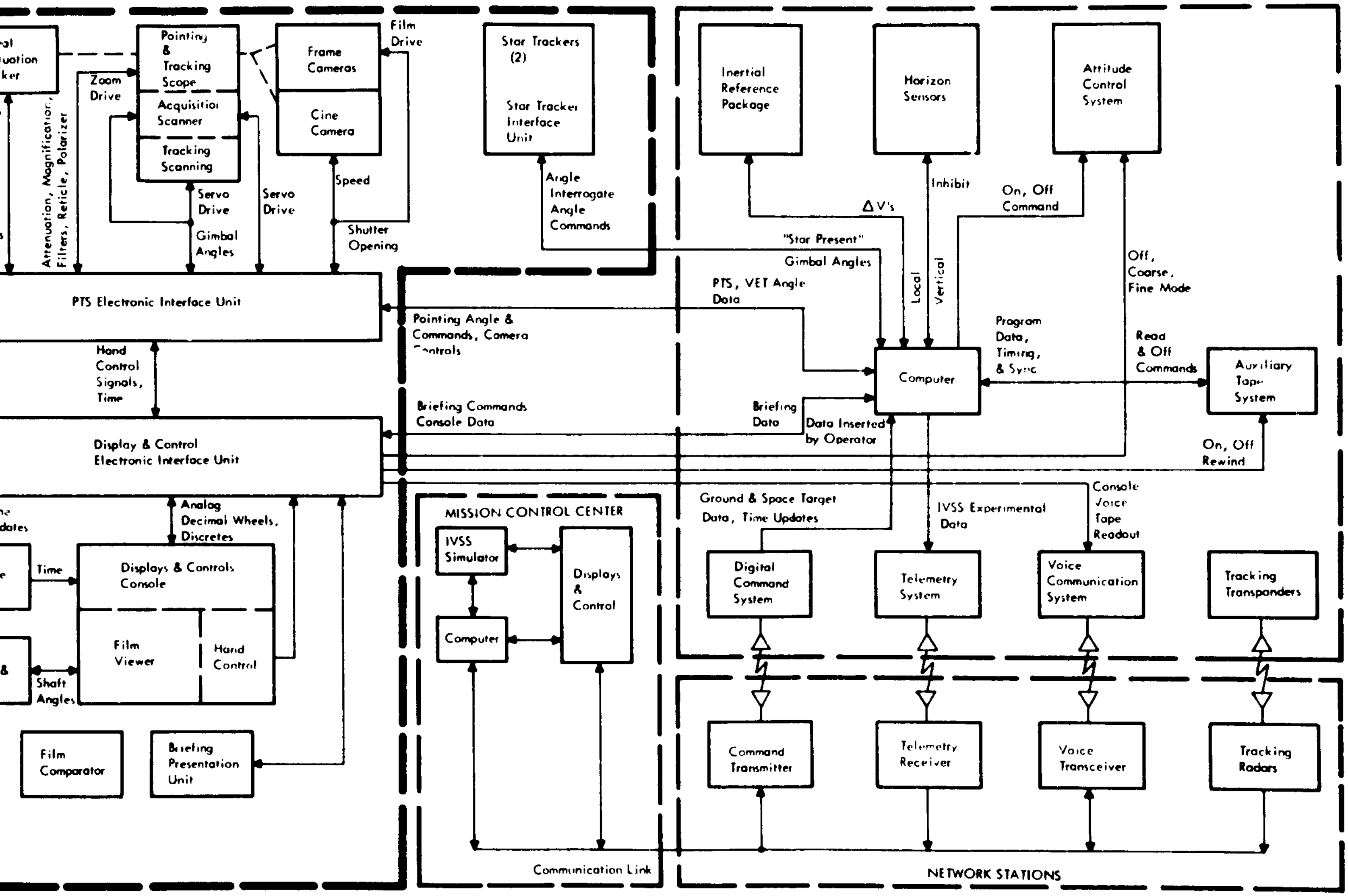
Figure 5.1 is the over-all block diagram of the IVSS-MOL equipment. The IVSS equipment can be logically subdivided into seven categories which, at this stage of the development program (preconceptual phase), are identified as contract end items (CEI). These CEI's are as follows:

- Pointing and tracking scope (PTS)
- Recording cameras
- Displays and controls
- Star trackers
- Experiment evaluation system
- Power supply
- AVE software

The PTS CEI contains the tracking scanners, the acquisition scanners, the telescopic system, and the pointing and tracking scope electronic interface unit. Also included in the PTS is the visual evaluation tracker (VET), which is replaceable, depending upon the inclusion of the P-11 and P-12 experiments. The performance of the PTS and astronaut is recorded using the two frame cameras having frame rates from 1 to 4 frames per second, and the cine camera capable of frame rates from 4 to 40 per second. These cameras make up the recording camera CEI and are interchangeable. The cine camera, however, would only be mounted on the high magnification relay optics. The frame cameras could be mounted on within the high- or low-magnification relay optics. Also included in the recording cameras CEI is the data block that essentially identifies the frame and data-tags the exposed film.

The displays and controls CEI is composed of a console, a briefing presentation unit, briefing material andfilm file, filmviewer, a time reference unit, and an electronic interface unit. The major portions of the console


IVSS EXPERIMENT EQUIPMENT
Visual Evaluation Tracker
Pointing & Tracking Scope
Acquisition Scanner
Tracking Scanning
Frame Cameras
Cine Camera
Film Drive
Zoom Drive
Servo Drive
Film Processor
Attenuation, Magnification, Filters, Reticle, Polarizer
Servo Drive
Servo Drive
Gimbal Angles
Speed
Shutter Opening
On-Off Film Drive
Shaft Angles
Spacecraft +28 VDC
Power Supply System
Regulated & Unregulated Power to all IVSS Equipments
PTS Electronic Interface Unit
Pointing Angle & Commands, Camera Controls
Hand Control Signals, Time
Briefing Commands Console Data
Display & Control Electronic Interface Unit
MISSION CO
IVSS Simulator
Computer
Clock
Time Updates
Analog Decimal Wheels, Discretes
Time Reference Unit
Time
Displays & Controls Console
Film Viewer
Hand Control
Briefing Material & Film File
Shaft Angles
Film Comparator
Briefing Presentation Unit



2

Figure 5-1 Interlaced IVSS-MOL Block Diagram

are made up of the hand control, the voice recorder, the VET control panel, the malfunction control panel, and the PTS controls. The PTS controls are required for zoom magnification, changing filters, reticles, and orientation of the driftmeter grid reticle.

The startracker CEI is required only for multi-target tracking and for that reason is included here as part of the IVSS equipment. The experiment evaluation system CEI is made up of two units: the film comparator by which the astronaut's performance could be evaluated in space, and the film processor, whereby the astronaut would process all of the exposed film.

The power-supply interfaces with the 28 VDC off the vehicle bus and regulates it to meet the requirements of the IVSS equipment.

The aerospace vehicle equipment (AVE) software system CEI will consist of: (1) maintenance manuals; (2) operational procedures manuals (such as for setting up, running and evaluating the experiments; and (3) tapes for conducting the experiment, (i. e. loading the computer storage for diagnostic checkout and operation of the experiment). Also included as part of the AVE software, is the briefing material for pre-assigned ground targets. (Briefing material, especially of relatively inaccessible targets, might be generated in space as part of the IVSS experiment. This could be a more selective approach using higher quality optics than have been developed to date.)

The above IVSS equipment interfaces with the MOL vehicle equipment and subsystems: the inertial reference package, horizon sensors, and the attitude control system (which could be turned off at the beginning of the tracking run to preclude transients during the high-magnification tracking mode). The central data processor will have a digital interface with the IVSS equipment through the two electronic interface units associated with the PTS and the displays and controls. The auxiliary tape storage system contains the tapes for loading the computer with the four IVSS programs. The computer, using the digital command system and the telemetry system, would tie into the ground support stations. Descriptions of the communications and data management systems in the vehicle and the ground support networks are provided in Sections 5. 3 and 5. 4.

The IVSS requirement listed is capable of three distinct modes of operation:

- Primary Mode - a digital instrumentation that meets the criteria for tracking a single target.

- Analog Mode - an analog instrumentation that meets the criteria for tracking a single target.
- Extended Capability Mode - a digital instrumentation that employs the startracker for tracking multiple targets.

The associated digital computer requirements are discussed later in this section (and appear in Table 5-14).

5.1.1.2 Candidate Optical Configuration

The PTS candidate optical configuration is shown in Figure 4-13 (optical schematic) and in Figure 5-2 (mechanical schematic). Table 5-1 lists the general properties of the candidate optical configuration, which is described herein.

The Pointing-Tracking Scope will give the astronaut operator and observer the capability of viewing a near hemisphere with computer-supported optics and a low to high magnification capability. The system shall be capable of pointing and tracking in two axes (pitch and roll) and is both automatically and nominally controllable.

5.1.1.2.1 Pointing and Tracking Scope (PTS) — The PTS optical system will consist of: (1) the inner periscope assembly; (2) the high-power scanning pedestal; (3) the low-power scanning pedestal; and (4) the PTS spacecraft coupling structure.

An eye piece will be provided for the operator, who will have both high- and low-power objective access. An eyepiece will also be provided for the observer, who will have low-power objective access only, regardless of the system in use by the operator. The space available for installation of the PTS periscope is a radial rectangle, with one side along the skin, 1 × 6 feet, with the long axis parallel to the roll axis of the vehicle. The space will extend 3 feet inward, thus forming a 18-cubic-foot box. There will be a maximum projection outside the skin of 1 foot radially. There will be two objectives, a low and high power, with an eyepiece magnification range of 1.5 to 108. The low-power system will have a range of 1.5 to 9, and the high power system will have a range of 18 to 108.

5.1.1.2.2 Inner Periscope Assembly — This section of the system includes the image forming optics, optical relays, optical switching systems, and the visual evaluation tracking simulator. The optical components shall be maintained at 68 ±2°F in order to not degrade the acuity of the system.

The low-power objective will be a 37.5 mm f/2 lens with a first image plane resolution of 8 arc sec on a three-bar target with a range of light

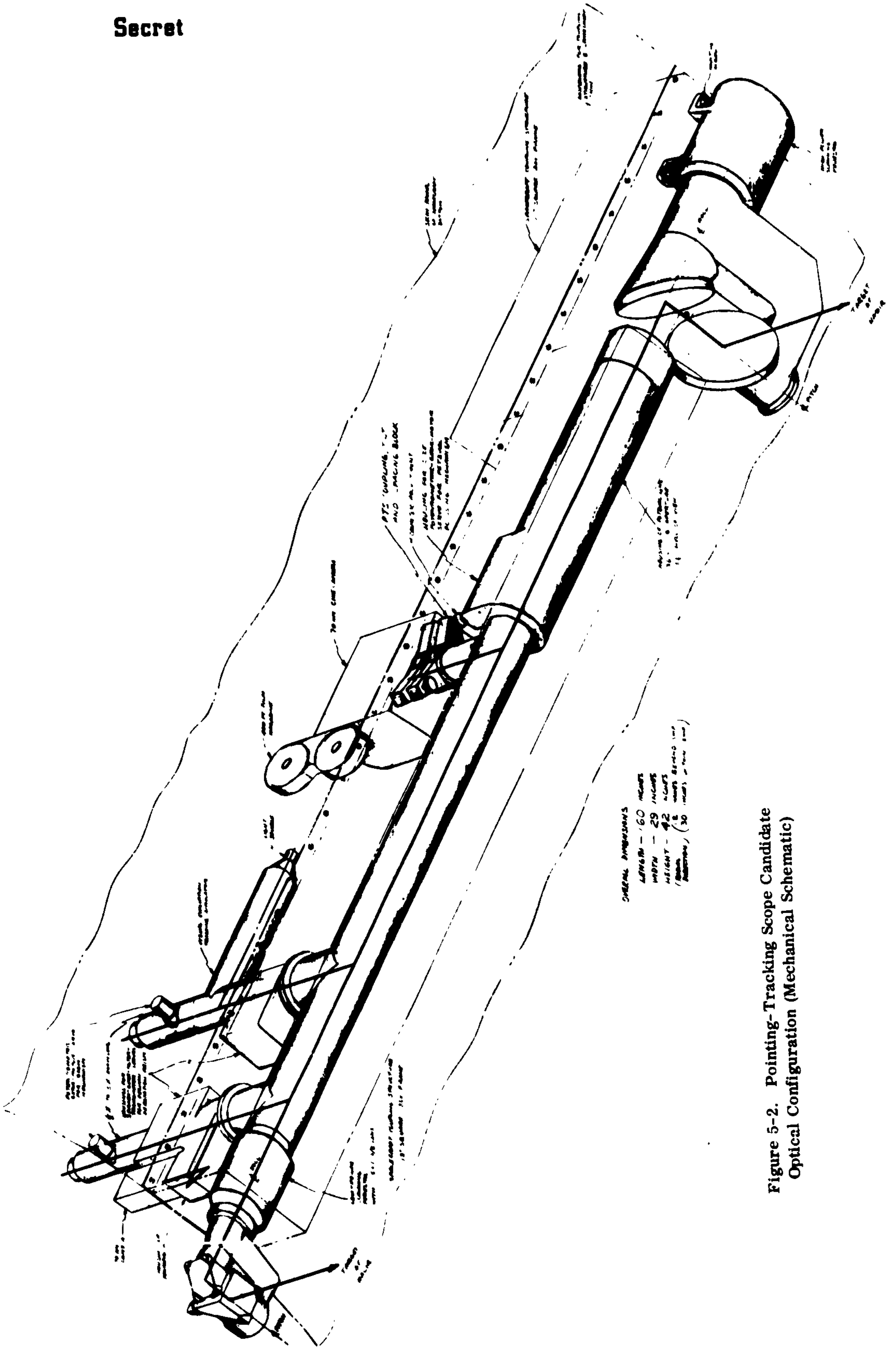


Figure 5-2. Pointing-Tracking Scope Candidate Optical Configuration (Mechanical Schematic)

Table 5-1

POINTING-TRACKING SCOPE CANDIDATE OPTICAL CONFIGURATION GENERAL PROPERTIES

Wide-Field System (Acquisition)	Magnification range: 1.5 to 9.0 × 300 m Objective focal length: 1.5 in. Exit pupil dia.: 13 to 2 mm. Real field angle: 30 to 5 degrees Objective diameter: 0.75 in. Apparent field angle: 45 degrees
High Magnification System (Pointing-Tracking)	Magnification range: 18 to 108 × 300 m Objective focal length: 36 in. Exit pupil dia.: 11 to 2 mm. Photographic field angle: 30 degrees At 160 n mi altitude, photo ground coverage: 85 n mi diameter Scale factor: 17,680,000 Real field angle: 2.5 to 0.4 degrees Objective diameter: 8.0 in. Photographic field angle: 3.6 degrees At 160 n mi altitude, photo ground coverage: 10 n mi diameter Scale number: 320,000 Apparent field angle: 45 degrees
Scanners	Roll-pitch gimbals: For acquisition, two 45 to 90-degree prisms; for pointing, tracking, two 45-degree elliptical mirrors
Camera (Frame)	Film size: 70 mm Format size: 2.25 in. diameter Frame rate: 1-4 fps Focal plane shutter: 1 to 1/1000 sec
Camera (Cine)	Film size: 70 mm Format size: 2.25 in. diameter Frame rate: 4-60 fps Disc shutter: 1/25 to 1/1000 sec.
Film	Kodak Special High-Definition Aerial Film, Type SO-243
In-flight Processing	Kodak Bimat Process

to adjust the focal distance from infinity to 500 feet (minimum distance).

There will be electronic remote control of all optical switching, derotating, and focus systems.

There will be automatic operator eyepiece zoom fly-back to minimum eyepiece effective focal length upon change from low- to high-power objective.

5.1.1.2.3 Low-Power Scanning Pedestal — The low-power scanning pedestal will support and drive the reflecting elements which direct the line of sight over the near hemisphere field (defined as the field from nadir to 80 degrees above nadir) in all directions.

The scan elements will form a two-axis system with pitch and roll gimbals. The roll axis will be parallel to the spacecraft roll axis, and the pitch axis will be orthogonal to that axis, with the LOS moving fore and aft.

A pedestal base attached to the spacecraft coupling structure will support the roll arm, roll arm drives, bearings, and angular read-out.

Angular read-out will be to 1 arc min, and alignment of the low-power system LOS with the high-power system LOS will be within 5 arc min (static).

The pitch arm will contain and support the pitch drive, bearings, and angular read-out. The pitch arm will be attached to the roll arm in such a manner as to allow the full 30-degree field angle to be unobscured by structures over a maximum of the required scan field. The reflecting elements, mounted on the roll and pitch arm, will not degrade the image beyond tolerance levels because of vibration or misalignment during operation. Further the optical quality of the reflecting elements will be such that the resulting wave front is maintained to a 1/8-wave distortion.

5.1.1.2.4 High-Power Scanning Pedestal — The high-power scanning pedestal will support and drive the reflecting elements which direct the LOS over the near hemisphere field (defined as the field from nadir to 80 degrees above nadir) in all directions.

The scan elements will form a two-axis system with pitch and roll gimbals as defined for the low-power scan pedestal. The two scan systems will be slaved, with the high-power system as the master system.

A pedestal base attached to the spacecraft coupling structure will support the roll arm, roll arm drives, bearings, and angular read-out.

The pitch arm will contain and support the pitch drive, bearings, and angular read-out. The pitch arm will be attached to the roll arm in such a manner as to allow the full 3.6-degree field angle of the objective to be unobscured by structures over a maximum of the required scan field. In any case, no full obstruction in this field will be allowed.

The reflecting elements, mounted on roll and pitch arms, will not degrade the image beyond tolerance levels because of vibration or misalignment during operation.

The reflecting elements shall be of such quality that the reflected wave front is maintained with 1/10-wave distortion over the 8-inch objective aperture.

The angular read-out shall be accurate within 5 $\widehat{sec}$ and must be referenced within 5 arc sec to the vehicle axes (dynamic). The read-out shall be in digital form for processing by the coordinate converter and computer. The servo systems shall have a 6-cycle minimum bandwidth. The servo system shall be a man-aided closed loop with the computer as the signal generator. The candidate digital and analog servo systems have been shown in Figures 4-14 and 4-16.

5.1.1.2.6 PTS Spacecraft Coupling Structure — The scanning pedestals, and such other components of the system as may extend outside the skin of the vehicle, are constrained to a radial distance of 1 foot beyond the skin. All elements which are so located shall be attached to the PTS spacecraft coupling structure. This structure will be so designed as to maintain those tolerances required to permit the angular accuracies called for in the system. The maintenance of a safe pressure seal is a function of this structure. It will also serve as the optical system base-plate, and tolerances will be measured with respect to this structure.

Optical windows will be provided as an interface with the space environment as part of this structure. No window will degrade the transmitted wave front over the aperture of its respective lens beyond 1/10 wave.

Sun sensors will determine when the PTS LOS is directed toward the sun. A signal will be generated when the sun is within 10 degrees of the axis of the main scanner and within 40 degrees of the axis of the auxiliary scanner, dropping a sun shade in the optics of the PTS.

The sun sensor should be mounted on the pitch gimbal with an alignment of 1 degree (3σ) to the optical axis. The sensor shall have the following performance characteristics:

Field of view -	12 and 42 degrees, 1/2 core
Weight -	1.2 pounds, each
Accuracy at null -	20 arc min
Linearity -	±5% of 10 degrees output over ±10 degrees from null
Reliability -	0.9996 for 1 year
Environmental -	See Table 5-25

5.1.1.2.7 PTS Coupled Cameras – The PTS will have a camera station for each of the objectives. Both stations will be within the spacecraft, easily accessible for film or camera changing. The space occupied by the cameras is not included in the space restrictions previously noted.

The camera stations will be identical, with a spacing block to precisely locate the cameras for the best focus. The spacing block will be removable, and three micrometer adjusting screws will be provided so the operator can adjust position and tilt of the camera's focal planes. Replacement of the spacer block will return the system to the pre-set location. Three cameras will be provided for use with the system. All cameras will have identical mounting arrangements and focal plane positions.

Two of the cameras will be identical, light-weight-frame cameras with exposure rates up to 4 frames per second. The frame rate will be remotely adjustable from the operator's console. The frame cameras will have a capacity of 50 and 100 feet of perforated 70 mm film in a removable magazine. The cameras will permit easy manual filter change. The filters will be replaced with an equivalent clear glass slide to avoid focal plane changes. A focal plane shutter will be provided with an exposure range of 1 to 1/1000 seconds, with stops at 1/10, 1/15, 1/100, 1/250, and 1/500 second. The maximum weight of the frame camera and 50 feet of film shall not exceed 8 pounds.

One camera will be provided on an optional basis, which has a cine capability (frame register for projection without image displacement). The cine camera shall have rates from 4 to 60 frames per second. The camera will be designed to provide pin registration at frame rates up to 60 per second. The frame rate will be remotely adjustable from the operator's console. The cine camera will have film capacity of 100, 200, and 400 feet in a removable two-compartment magazine that can be removed before the film is completely used. This camera will have its film plane location and mounting arrangements identical with the frame cameras. The cine camera will permit easy manual filter changes. A clear glass slide will be provided when the filter is not used to preclude changes in focal distance. The maximum weight of the cine camera with a 100-foot film magazine shall be 80 pounds.

A disk-type, focal-plane shutter shall be used, with provision for easy replacement of the shutter disk, so that multiple exposures can be made on each frame. The disk shutter shall be adjustable to provide a range of exposure from 1/25 to 1/1000 second.

5.1.1.2.8 PTS Data Block — The IVSS data recording system will include records of pertinent facts exposed in the unused corners of the

70 mm format of both cameras. Each frame will thus be a complete record of the events at that instant, both in imagery and the conditions under which the imagery was recorded. The data to be recorded is as follows:

- Angular position roll and pitch (19 digital bits)
- Angular rate roll and pitch (19 digital bits)
- Time (milliseconds)
- Day, month, year, film - data card
- Magnification
- Sensitometer strips - full spectrum photographic, visual, minus blue photographic.

These data will be presented in a data plane for optical relay into the film plane of the cameras.

A data block structure and coupling mechanism will be provided for attachment to the optical structure. The data block will require signal processing and display illumination electronics, which will be contained in the IPS structure. The data displays must be illuminated to a level of at least 1 foot-lambert. The sensitometer strips will have a rear illumination, collimated variable-intensity light source.

5.1.1.2.9 Visual Evaluation Tracker — The visual evaluation tracker is to be a detachable projector which, when installed, will project an image of the movable target into the focal plane of the right eyepiece. The target is moved in the X and Y direction by computer-controlled servos. The interchangeable targets can be transparency frames or aperture discs. The optical elements consist of light source, condenser lens, projection lens, and flip mirror.

5.1.1.3 Display and Control Subsystem

The display and control subsystem consists of four major functional components:

- Display and Control Console
- Briefing Presentation Unit
- Briefing Material and Film File
- Time Reference Unit

5.1.1.3.1 Display and Control Console — The IVSS display and control console, which interfaces with almost every IVSS subsystem, is important not only from the experiment performance viewpoint, but also due to its multi-interface functions. The console layout, shown in Figure 4-17 gives some indication of the interfacing required.

The proposed console will generate approximately 150 discrete signals and 10 analog signals, and will have approximately 56 display wheels and

three thumb-wheels. Because of the multiple display wheels, it will probably be advisable to use a programmable formatter to drive one wheel at a time. By using the formatter, a single interfacing may be used for all the display wheels. The analog interface with the console is one analog-to-digital encoder, most probably seven bits. Each switch and set of display wheels are discussed in detail in Section 5.0 Volume IV, and, therefore, will not be repeated in this volume.

The estimated weight, volume, and power requirements for the display and control console are 100 pounds, 2 cubic feet, and 20 watts, respectively.

5.1.1.3.2 Briefing Presentation Unit — The unit used to present the briefing film to the PTS operator should be able to show the briefed target in the same perspective as the live target will be viewed. For close inspection of particular areas of the film, it is also desirable to have a magnification capability in the briefing unit.

The unit selected for the briefing presentation unit will have servo drives (controlled by either the computer or manually through the hand control) for rotating the film and representing it in oblique perspective. A 25-watt light source will provide the necessary light for film viewing. There will be three magnifications: 1X, 2X, and 3X. It is anticipated that the unit will handle a 25-foot roll of film for each briefing. This unit, which will be installed in the console area, is expected to require 45 watts average power, weigh 16 pounds, and occupy 0.8 cubic foot of space.

5.1.1.3.3 Briefing Material and Film File — A file for storing exposed and unexposed film, and the processing material, must be provided for use during the IVSS experiment because of the voluminous amounts of film needed for satisfactory performance of the experiment. This file should be easily accessible to the crew member. The file should be capable of holding approximately 5000 feet of unexposed film, 500 feet of briefing film, and enough processing material for the unexposed film.

The file is expected to weigh 90 pounds (including the film) and occupy 1.5 cubic feet of space.

5.1.1.3.4 Time Reference Unit - The IVSS experiment time requirements are broken into two separate categories, elapsed time between photographs and Greenwich Mean Time (GMT).

The elapsed time between photographs places the most stringent requirements on the time source. Taking a minimum interval of 1 second between pictures for IMC evaluation, a clock with a short term (1-second) stability of one part in a million would contribute virtually no error to IMC.

Clock long-term stability (GMT) requirements are reflected in ephemeris accuracy. If it is desirable to have knowledge of vehicle position to within 500 feet, the error contribution due to inaccurate knowledge of time should be under 50 feet. A time error of 1 ms would contribute approximately a 25-foot position error, which is acceptable.

Based on present technology, two types of clocks could be used for the IVSS time source: an atomic clock or a quartz oscillator. Although atomic clocks are highly accurate, their weight and reliability are inferior when compared to quartz oscillators, which are small, lightweight, and highly reliable.

Quartz oscillators used for time references have two sources of error: drift and frequency setting. The effects of these errors as a function of time are shown in Figure 5-3, which shows that a drift rate and frequency setting error of one part in 10^8 results in approximately a 1 ms error after 1 day. Consequently, digital command system time updates provided once a day with a reset accuracy of 1 ms during the MOL mission would enable the GMT requirement to be met. Since this drift rate and setting error are easily achievable with state-of-the-art components, there should be no problem in attaining this accuracy.

The short term stability of one part in one million is also compatible with the long-term stability requirements stated above, and poses no additional timing problems.

A system capable of meeting the short- and long-term stability requirements would weigh under 5 pounds, occupy approximately 150 cubic inches, and consume an average of 2 to 3 watts of power.

5.1.1.4 Star Tracker

The star tracker consists of an optical-mechanical package and a tracker electronic package, which include the digital or analog read-out device. Together these components provide the capability to track second-magnitude stars, read out the gimbal angles, and point the tracker telescope to a commanded angle within its gimbal freedom.

The optical-mechanical package consists of a telescope mounted in a two-gimbal pitch-roll system. The optical system generally consists of an off-axis, parabolic, vibrating-reed scanner and photomultiplier tube. The multiplier tube and electronics generate X and Y coordinated d-c error signals proportional to the boresight axis and the star line. The gimbal drives are directly coupled to d-c torque motors. Position transducers are mounted on the two gimbals to give gimbal shaft angle positions.

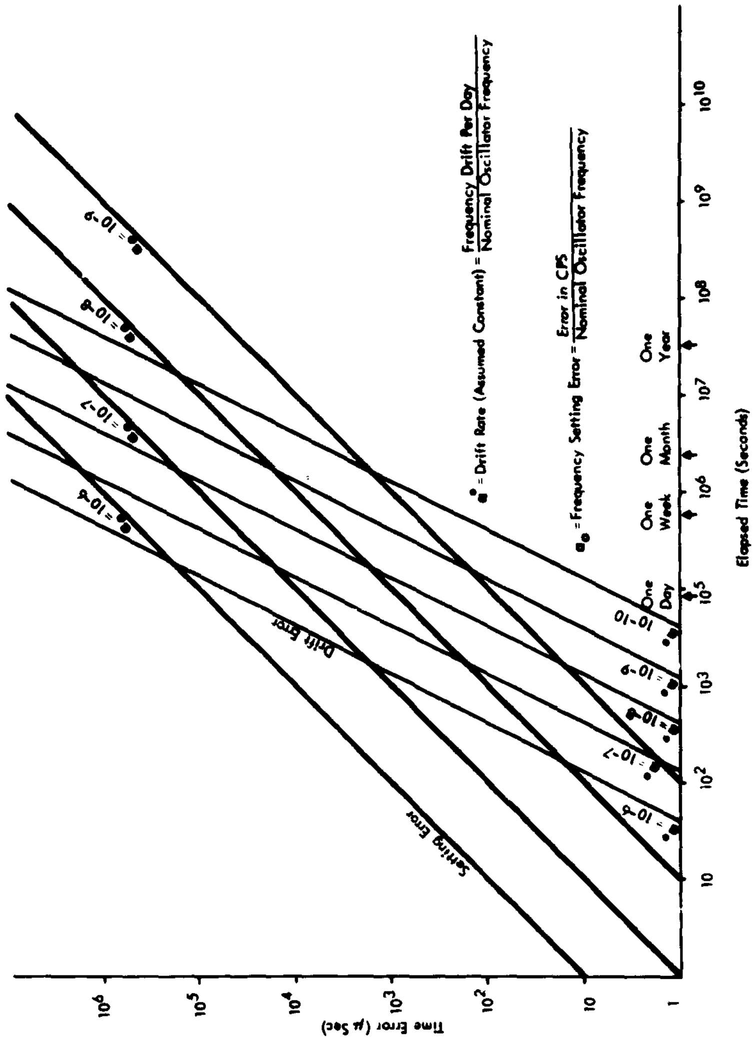


Figure 5-3 Effect of Drift and Frequency Setting Errors

The following required performance characteristics are well within current state-of-the-art:

- Star recognition - 2.0 magnitude and brighter in a 1 degree field, rejecting stars of 3.0 magnitude or dimmer.
- Star Tracking Null - The star tracker will indicate tracking null when the sum of the two gimbal angle errors is equal to or less than 4 arc min.
- Discretes - Star presence and star tracking signals.
- Tracking Angle - ±60 degrees about each gimbal.
- Acquisition - "Lock-on" occurs as apparent star approaches within 0.4 degree of field of view when the rate is less than 0.35 degree per sec.
- Tracking - The maximum angular rate while tracking is approximately 0.5 degree per sec, and the maximum acceleration is 0.045 degree per sec^2.
- Accuracy - The composite tracking error will not exceed 20 arc sec (1σ).
- Reliability - Approximately 0.95 for continuous use in orbit for 1 year.
- Physical Characteristics - weight, 30 pounds; power, 15 watts; volume, 1.0 cubic foot (including electronics, digital read-outs, and heaters).

The star tracker in the IVSS system would only be used in the extended capability mode to maintain an accurate celestial attitude reference. It should be mounted on the PTS base plate and aligned to ±20 arc sec (3σ) with the PTS gimbal axes to assure accurate pointing and ephermeris updating. It is possible that an auto-collimator may be needed to align the star tracker to the PTS after launch of the MOL.

5.1.1.5 Experiment Evaluation Subsystem

The equipment used to evaluate the results of the IVSS experiments must at least have the accuracy required to determine whether man is performing image motion compensation to the specified level of accuracy. Two separate areas must therefore be considered in the evaluation subsystem: the type of film processing used and the measurement devices used.

A film processor that will develop the exposed film without degrading the photographed target is a definite requirement. However, the weightless and enclosed environment of the MOL poses problems not usually found in film processing, and dictates the use of web monobath technique such as the Bimat process. This technique essentially consists of bringing a

pre-treated material in contact with the film in the processor for a specified period of time, during which time the film is processed to completion. This type of processing, called "dry" processing, may impact the MOL life environmental control unit because toxic fumes may be released during the process. The toxicity problem, if any, must be thoroughly investigated during the next phase of the IVSS study. If the results of this study show the fumes released are dangerous, a special venting system must be designed for the processor.

The measurement device used is greatly impacted by the IMC requirements. Based on the error analysis and evaluation requirements presented in Volume IV, it is necessary to measure distances on the developed film to approximately 1 micron. This requirement indicates that an ultra-high-precision photo measuring device, such as the Mann 829C comparator, must be used in MOL as part of the IVSS equipment. The latter device, which incorporates a microscope with an image magnification of 50X, has excess capability in area measurement (100 mm × 150 mm), since 70 mm film will be used.

In addition, it is highly desirable to provide some type of film projection device that will allow the observer to scan the entire photograph for interesting or unusual targets. To provide this capability, a film projection screen, 9 × 9 inches with a 100-watt light source and appropriate lenses, has been included in the console area.

5.1.1.6 Power Supply Subsystem

The power supply subsystem is constrained by the requirement for it to interface with almost every IVSS subsystem, and thus figures strongly in over-all system evaluations from the standpoint of reliability, efficiency, weight, and general probability of mission success. The basic problem in designing the IVSS power conditioning equipment is not one of matching interfaces already established, but to use power supply technology early enough in system design to allow optimization of the power supply subsystem.

There are two basic types of power conditioning equipment which can be used for supplying regulated power to IVSS subsystems.

The series-pass-type of regulation scheme has very low efficiency when input voltages to the regulator vary appreciably and when low voltages and high currents must be regulated. Since IVSS equipment power requirements are in this latter category, series-pass regulation was rejected.

Pulse-width modulation is presently used in Gemini and Apollo equipment. There are two approaches possible with pulse-width modulation:

- Series-type pulse-width modulator followed by a d-c to d-c converter, providing multiple outputs with 2 to 5 percent regulation.
- Pulse-width controlled d-c to d-c converter. A separate regulation unit for each output voltage is required, but regulation under 1 percent is achievable.

Based on the time reference unit and PTS and startracker servo requirements for voltages regulated under 1 percent, it appears that separate pulse-wdith-controlled d-c to d-c converters for critical servo voltages are necessary. Other equipment, such as the VET and cameras, will probably use one series-type pulsewidth modulator for regulation of all required voltages. Block diagrams of the two pulse width modulators are shown in Figure 5-4.

The over-all power requirements for the different IVSS equipments are listed in Table 5-2. The power supply unit is expected to weigh 35 to 40 pounds, and occupy approximately 500 cubic inches.

5.1.1.7 AVE Software

The software requirements for IVSS experiments encompass areas such as the auxiliary tape program storage for the experiments, preparation of briefing films, maintenance and operation manuals. Because of the critical nature of the computer functions in both control of, and computation during the IVSS experiments, the computer programs must be optimized for minimum program time, maximum accuracy consistent with need, and maximum use of subroutines consistent with storage requirements. All programming, briefing film preparation, and manuals should be in final form well in advance of final IVSS system production to permit the use of simulators for check-out and hardware design tradeoffs.

5.1.2 Performance Prediction

This subsection presents the predictions of the precision, reliability, and maintainability associated with the IVSS.

5.1.2.1 Precision

For the error isolation discussion, the pointing and rate errors during the four servo computer modes of operation (Section 4.2) are presented.

Tables 5-3 and 5-4 lists the pertinent error sources of the system which comprise the following:

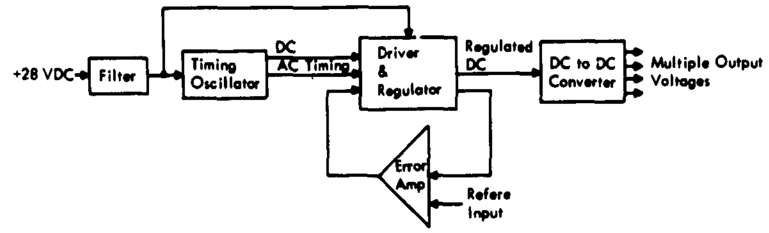
- Absolute static pointing accuracy
- Relative pointing accuracy under dynamic pointing conditions

Table 5-2

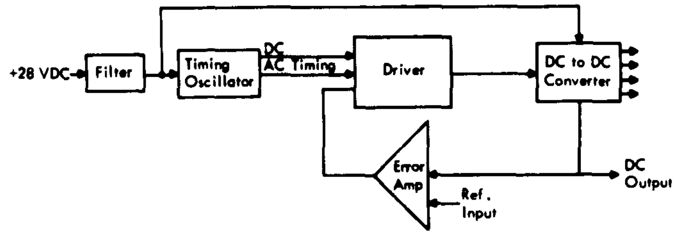
IVSS EQUIPMENT POWER REQUIREMENTS

Unit	Peak Power (watts)	Average Power (watts)
PTS Tracking Servo System	362	122
PTS Acquisition Servo System	120	60
Derotation and Auxiliary Derotation Servos	120	60
Zoom and Reticle Servos	35	24
Startrackers (2)	60	30
Cine Camera	200	50
Frame Cameras	200	10
Controls and Displays	20	20
Film Viewer	125	125
Film Comparator	8	8
Briefing Presentation Units	49	45
Time Reference Unit	3	3
Electronic Interface Units	10	10
VET	49	45
Totals*	1,361	612
Regulation losses (65% efficiency)	-	205
Total average input power to IVSS equipment*		817 watts

*The total peak and average powers given in this table are indicative of power consumption with all equipment "on", which is highly improbable. Power profiles for typical experiments are given in Volume IV, Section 3.4.



a) Series Type Pulse Width Modulation Followed By DC to DC Converter



b) Pulse Width Controlled DC to DC Converter

Figure 5-4 Pulse-Width Modulation Schemes

- Absolute dynamic pointing accuracy
- Rate errors.

The results of the experiment can be evaluated reasonably well, down to 0.05 percent of the LOS angular rate. This assumes photogrammetric measurement errors corresponding to 0.01 percent. This requires sampling times between verification photos of about 5 seconds. The evaluation of man's discrete pointing accuracy while tracking can be considered better than 2.5 arc seconds.

The absolute static pointing error is the error between the indicated LOS at the mounting pedestal, and the actual LOS from the pedestal to the target.

The relative pointing accuracy under dynamic conditions just considers the errors that the man would see in his eyepiece when fixing on a moving target.

Table 5-3
IVSS ESTIMATED MAXIMUM POINTING PRECISION (In Seconds, Max)

Error Sources	Initial Pointing	Absolute Static Pointing		Relative Pointing Modes 2 & 3		Absolute Dynamic Pointing Mode 4		Remarks
		*	**	*	**	*	**	
Man	Not	±45	±45	±45	±45	±45	±45	E.S.S. Data
Servo Static		±5	±5	—	—	—	—	See Servo Section
Servo Dynamic	Critical	—	—	±10	±10	±10	±10	
Optical Axis Missalign		±3.0	±2.0			±3.0	±2.0	Estimated (0.0005" disp)
Reticle-to-Optical Axis	Degrees	±4.0	±2.0			±4.0	±2.0	Estimated (0.0005" disp)
Mechanical Mounting		±70	±17			±70	±17	Itek Data
Pitch Mirrior Align	o.k.	±37	± 9			±37	± 9	Itek Data
Mechanical Bearing						±20	± 5	Itek Data
Pitch-Roll Axes Non-Orthorganality						±14	± 4	Itek Data
Inertial Reference Align						±15	±10	From Vendor Brochure
Inertial Reference Noise						±60	±4.0	
Computer and Equation Errors						±10	± 5	In-House Data and Est.
RSS (1σ)		30	17	16	16	38	21	

* Off the Shelf
** State of the Art

Table 5-4
IVSS ESTIMATED RATE ERRORS (in $\widehat{\text{sec}}$/sec, max)

	Other Modes	Extended Capability Mode	Remarks
Servo Rate Error	±2 $\widehat{\text{sec}}$/sec	±2 $\widehat{\text{sec}}$/sec	Kv = 4000
Computer Quantization	±30 $\widehat{\text{sec}}$/sec	±30 $\widehat{\text{sec}}$/sec	over 1/5000 sec time
Man or Instrumentation	±3 $\widehat{\text{sec}}$/sec	±2.5 $\widehat{\text{sec}}$/sec	From E.S.S. Data & 7090 Sim.
RSS (1σ)	1.2 $\widehat{\text{sec}}$/sec	1.1 $\widehat{\text{sec}}$/sec	Computer Quantization Negligible with Evaluation ≥ 0.01 sec.

The absolute dynamic pointing accuracy accounts for the errors that should be considered when fixing on a target to update the ephemeris of the space vehicle. This error is the difference between the indicated LOS at the mounting pedestal and the actual LOS from the pedestal to the target under conditions of motion around the nadir position.

The mechanical tolerances were based on the capability of Itek's manufacturing facility and are referred to as either: Standard precision tolerances or limit precision tolerances. The former would be approximately ±0.0002 inch per foot, obtainable with routine use of a Lindner of Moore jig borer, a Hardinge Precision Lathe, a DeVlig horizontal boring mill, or grinding, lapping, and boring machines.

Limit precision tolerances would be approximately ± 0.00005 inch per foot, obtainable for bores and flat surfaces with careful use of the best machines, such as the Lindner, Moore, and DeVlig, all of which are self-measuring. The Hardinge lathe and MSO cyclindrical grinder would be used for ± 0.00005-inch tolerances on outside diameters.

Table 5-5 presents a preliminary listing of the mechanical tolerances.

5.1.2.2 Reliability Prediction

Table 5-6 presents the MTBF estimates for each of the IVSS contract end items.

5.1.2.2.1 Duty Cycle – Reliability is computed using a 60-hour mission time, where the mission includes both the boost and the orbital phase. Derivation of the 60-hour time period is now explained.

IVSS mission experiment time is estimated to be 85 hours, of which approximately 45 hours are allocated to the performance of experiments. The remaining time will be devoted to on-board analysis of experiment results. The PTS and related equipment will be operated "on" only when experiments are being performed. Therefore, 45 hours has been selected as an average orbital time base.

Since the IVSS is not required during boost, transient electrical failures, even if the equipment were energized, are not detrimental. Because of this, a stress factor of 60 was used in lieu of 500 as indicated in the system effectiveness guide, Report No. TOR-469(5107-30)-2. Assuming a 0.25-hour boost phase, a time increment of 15 hours must be added to the orbital operate time.

5.1.2.2.2 Subsystem Reliability – The reliability of the primary IVSS subsystem is 0.943 (probability of success) for a 60 hour mission time. The corresponding reliability for extended capability (Mode 4) is 0.932. Figure 5-5 presents the reliability diagram used in this analysis.

The cameras are indicated as a redundancy in the reliability diagram, since failure of one (and possible two) produce, at worst, only a nuisance condition. Full capability reliability i.e., the three cameras considered with the rest of the subsystem, results in 0.938 probability of success.

Consideration of the VET operation as a separate mode of operation effectively removes it from the basic system. Exclusive of the VET the primary IVSS mode has a 0.949 mission reliability.

To provide an indication of IVSS mode reliability potential, the following conditions are assumed:

- Operating manually or without the derotation, spectral filter, attenuation, and polarizer PTS functions

Table 5-5

PRELIMINARY LIST OF MECHANICAL TOLERANCES

For Critical Surfaces Only; Based Upon Itek-Waltham's Capability

Part	High Power Optics	Standard Angular Tolerance (radians or arc seconds)
Pedestal	Mounting pads to jaw clutch	$\pm\frac{0.0002}{8} - 25\text{x}10^{-6}$ or (±5)
	Jaw clutch to roll bearing housing shoulder	± 0.0002/10.5 or (±3.8)
Roll Gimbal	Roll bearing shaft shoulder to jaw clutch	± 0.0002/10 or (±4)
	Jaw clutch to roll mirror mount	$\pm\frac{0.0004}{8.5}$ or (±9.4)
	Jaw clutch to pitch bearing housing shoulder	$\pm\frac{0.0002}{4}$ or (±10)
Pitch Gimbal	Pitch bearing shaft shoulder to jaw clutch	$\pm\frac{0.0002}{4}$ or (±10)
	Jaw clutch to pitch mirror mount	$\pm\frac{0.0004}{3}$ or (±27)
		Max Possible Error ± 70 arcseconds RSS Error - 32.8 arcseconds
Limit precision machining would result in 1/4 of this, or ±17 arcseconds.		

Misalignment Tolerances vs Lead Time

Misalignment between pitch and roll axes

±14 $\widehat{\text{sec}}$ off the shelf

±3.5 $\widehat{\text{sec}}$ 6-month delivery

Misalignment between pitch axis and pitch mirror:

±37 $\widehat{\text{sec}}$ off the shelf

± 9 $\widehat{\text{sec}}$ 6-month delivery

Runout of roll bearing; 4-point contact, 10-inch ID, 11-inch OD:

±25 $\widehat{\text{sec}}$ off the shelf

±13 $\widehat{\text{sec}}$ 3-month delivery

± 4 $\widehat{\text{sec}}$ 6-month delivery

Runout of pitch bearing; preloaded pair, 3 1/2-inch ID, 4 -/8-inch OD:

±23 $\widehat{\text{sec}}$ off the shelf

±11 $\widehat{\text{sec}}$ 3-month delivery

± 5 $\widehat{\text{sec}}$ 6-month delivery

Table 5-6
IVSS RELIABILITY

Item	MTBF (hours)
Pointing Tracking Scope	2,500
Recording Camera	11,800
Display and Control	2,000
Experiment Evaluation	28,500
Power Supply	25,000
IVSS Primary Mode MTBF	940 hours

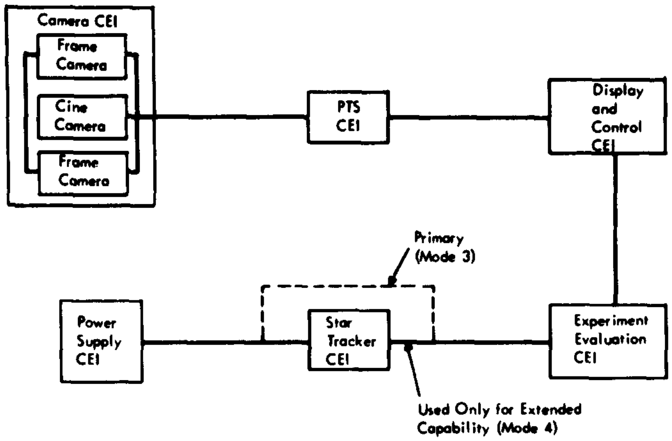


Figure 5-5 IVSS Reliability Diagram

- Considering only selected digital display read-outs essential, the remaining treated as nuisance
- Operation without the IVSS voice tape recorder
- Considering primary experiment objectives being accomplished without the star trackers
- Considering scanner encoder redundancy, this requires encoders being added to the acquisition scanner which are not indicated in the present pre-Phase I configuration.

IVSS reliability (60 hours) for the above degraded mode operation is estimated to be 0.968.

With the exception of the tracking scanner encoder bulbs, failure rates for projection lamps, and bulbs were not included in the MTBF estimates.

The external location and the importance of the encoders to the performance of all IVSS experiments warrants these bulbs being singled out as a critical degradation failure mode. Additional investigation of this item is planned as part of the Phase I activity.

5.1.2.3 Maintainability

5.1.2.3.1 In-Space Maintenance Concept — Present design of the IVSS will require provision for limited in-space maintenance to complement the predicted reliability and thereby maximize equipment availability for mission success. Maintenance actions will be restricted in time, skill required, and simplicity of execution. Limited fault diagnosis will be performed via computer-programmed automation, which will be aided as much as possible by the operator's observations and analysis. Ground backup analysis using vocal communication and telemetered computer data can be provided in difficult instances where on-board analysis is inconclusive.

Under the above constraints the estimated maintenance times have been computed* and are as follows:

- Daily scheduled maintenance time (SMT) = 15 minutes
- Mean time to repair (MTR) = 1.3 hours
- Average daily unscheduled maintenance time (UMT) = 6 minutes.

5.1.2.3.2 Scheduled Maintenance Time (SMT) — Scheduled maintenance will consist of calibration/alignment/check-out once every 24-hour period upon initial turn-on of the IVSS. Calibration, alignment, and check-out will complement each other as a total check. The operator will sight on a point target and by X-Y vernier adjustment from within the laboratory, bring the aim of the acquisition scanner spot image to agree with the aim of the tracking scanner.

The pointing and tracking telescope will be aligned to the star tracker by taking a fix with both on a star and entering the PTS scanner read-out factors into the computer memory for subsequent use. Camera functions of aperture control, shutter action, focus, film transport, and exposure control will be given a gross check by operator control, observation, and film evaluation. The resulting film can then be displayed on the film viewer to evaluate the film and check the viewer operation. All annunciator lights will be checked with a manually initiated lamp test.

* TOR-469(5107-30)-2, "Pre-Phase I System Effectiveness Guide," July 1964, Aerospace Corporation, Inc. (D. T. Romine).

The computer program utilized for automatic target acquisition and target tracking will also perform automatic malfunction detection and limited malfunction isolation, using lights on the control and display panels to display the results. Optimizing this malfunction detection and isolation capability will be pursued during Phase I as indicated in the maintainability program plan.

5.1.2.3.3 Mean Time to Repair (MTR) – The breakdown of this quantity is shown in Table 5.1.2-6.

5.1.2.3.4 Unscheduled Maintenance Time (UMT) – Unscheduled maintenance will be performed upon isolation of a malfunction detected during scheduled maintenance or normal IVSS operation. Malfunctions will be isolated by the complementary capabilities of operator observation and analysis, and computer programmed automation. Corrective action will consist of replacing burned out lamp bulbs, switching in of wired-in spares, such as a power supply, replacing a defective PTS servo motor, and replacing a defective electronic logic module.

Where on-board analysis or corrective action is ineffective, ground-based analysis will be utilized to usefully extend available maintenance time before inability to repair is acknowledged.

The determination of UMT can be conducted in one of two ways. From the previous reference,

$$UMT = 24 \lambda MTR,$$

From Section 5.1.2.2, the failure rate $\lambda = \frac{1}{MTBF}$ equals 1/800 hours. Therefore,

$$UMT = \frac{24 \times 78}{800} = 2.34 \text{ minutes/day.}$$

The second method of determining UMT is as as follows.
For $\lambda = 1/800$ operating time for the month duration, there is a 93 percent chance that no more than one failure will occur, while at the 99.8 percent confidence level, only two failures will occur. Using this latter figure

$$UMT = \frac{2 \text{ failures}}{30 \text{ days}} \times MTR = 5.2 \text{ minutes/day}$$

5.1.2.3.5 Spares – Spares to be carried on a mission will be selected on the basis of their individual reliabilities and their criticality to mission requirements. Consequently, a high confidence in maximum mission effectiveness will be realized. The following items will be stocked as spares:

- PTS servo motors (more study is required to finalize this item)

Table 5-7
MEAN TIME TO REPAIR BREAKDOWN

Schedule of Maintenance Functions		
Elapsed Time	Time for Each Function (minutes)	Function
7.5	7.5	Time to detect malfunctions (0.5 of SMT - 1/2 x 15 minutes). Either 0.5 SMT or time during normal IVSS operation for operator to detect malfunctions
15.5	8.0	Isolation via computer program automated annunciators or operator analysis
23.5	8.0	Switch in of wired-in spares or physically exchange offending pluggable module
31.0	7.5	Check IVSS operation, trouble not corrected
39.0	8.0	Isolation on second try
47.0	8.0	Corrective action of replacing faulty module
54.5	7.5	Second check, trouble not corrected
62.5	8.0	Isolation on third try
70.5	8.0	Corrective action of replacing faulty module
78.0	7.5	Third check of IVSS, operation successful
		78.0 minutes - 1.3 hours - MTR

- Camera
- Lamp bulbs
  (a) Annunciator
  (b) Scope and viewer illumination
  (c) Camera
- Power supply module
- Electronic logic module.

5.1.2.3.6 Repair Equipment — Since the repair task will be limited to switching in wired-in spares and to simple physical replacement of faulty items, only common hand tools (screwdrivers and wrenches) and several special insertion/extraction hand tools will be required.

5.1.2.3.7 Maintainability Improvement — During Phase I, as indicated in the maintainability plan (Volume V) design studies will be made to:

- Instrument the hardware with fault detection. This capability will be used with either manually conducted or computer programmed tests to improve fault isolation to the point of reducing predicted MTR to 0.7 hour.

- Design the PTS scanner assembly configuration to allow for replacement of servo motors, if possible
- Establish commonality within such groups as lamp bulbs, servo motors, electronic logic modules, or manual switches.

5.1.3 Physical Description of the IVSS Equipment

A summary for the IVSS equipment as described above, is presented in Table 5-8. The briefing material and film file, with a given weight of 90 pounds, may change if the film requirements change. The volume and weight for this file is for 25,000 frames of film and includes the processing materials, i.e., the web monobath materials to process half the film (12,000 frames).

The weights for the PTS and display and control panel are broken down further in Tables 5-9 and 5-10.

5.1.4 Critical Problem Areas

5.1.4.1 PTS Tracker Servo

The PTS tracker is probably the most critical subassembly of the IVSS. Image motion compensation will be accomplished only if the PTS performs to the design requirements specified in Section 2.0. These requirements point to a device that behaves like the combination of a very accurate speed control device for driving high-resolution film and a rate table such as is used to test low-drift gyros.

The tracking servo must be highly reliable and perform to the design requirements under the space conditions of (a) a vacuum environment, (b) high radiation levels, (c) extreme changes in temperature, and (d) zero gravity.

IBM investigations show that the tracking servo is a state-of-the-art device for space applications based upon the analytical studies and manufacturer's data. However, this should not be the sole proof considering the importance of the PTS performance to the mission. The next phase of the IVSS program should include a detailed investigation of the servos available so that a type fulfilling the requirements may be selected.

5.1.4.2 PTS Mechanical Design Problems

IBM studied the mechanical design of the IVSS PTS Periscope, with particular attention to how this design affected performance requirements. The investigation revealed many potential difficulties, all of which will require further investigation during the detailed study phase. These problems are subsequently enumerated and discussed in the order of decreasing difficulty.

Table 5-8
POWER, WEIGHT, AND VOLUME OF IVSS EQUIPMENT

Subsystem	Av. Power (watts)	Weight (lbs.)	Volume (cu. ft.)
Pointing and Tracking Scope (including scanner)	----*	312	15 (outside) vehicle 16.3 (inside)
Visual Evaluation Tracker	45	8	0.4
Frame Cameras (2)	10	12	0.5
**Cine Camera	50	80	1.0
Film Processor	----	10	0.5
PTS Electronic Interface Unit	271	25	0.5
**Star Trackers (2)	30	60	2.0
Briefing Material and Film File	----	90	1.5
Briefing Presentation Unit	45	16	0.8
Film Viewer	125	25	0.5
Film Comparator	8	25	1.0
Time Reference Unit	3	5	0.1
Displays and Controls Console	20	100	2.1
Display and Control Interface Unit	5	10	0.2
Power Supply Unit	205 regulation losses	40	0.3
TOTALS With Optional Equipment	817 watts	818 lbs.	42.7 cu. ft.
W/O Optional Equipment	737 watts	678 lbs.	39.7 cu. ft.

* Power for PTS servos included in PTS electronic interface unit.

** Denotes Optional Equipment

Table 5-9
PTS UNIT WEIGHT

Unit	Weight (lbs.)
Scanner	85
Telescope (Inside)	56
Telescope (Outside)	64
Baseplate	87
TOTAL	292

Table 5-10
DISPLAY AND CONTROL CONSOLE WEIGHT

Unit	Weight (lbs.)
Console Plate (Sub-Units Removed)	10
Subunits	70
Connectors	10
Harness, Miscellaneous	10
TOTAL	100

5.1.4.2.1 Determination of the Operational Temperature Range of Individual Components - Extreme temperature variations occur in space vehicles, especially when they have complex shapes, and orbit partly in sunshine and partly in earthshine. Heat sources within these space objects increase the difficulties involved with analyzing the temperature variations and their effects on mechanical properties. Minimum temperatures are of great interest because the lubrication of sliding and rolling surfaces becomes very difficult at temperatures less than -100°F. In addition, the properties of materials at extremely low temperatures vary greatly from those noted in a "normal" earth environment. The high temperatures spacecrafts encounter in sunshine could affect lubrication by increasing volatilization rates, which are already extremely high due to the nearly perfect vacuum at orbital altitudes. Temperature ranges also determine thermal contraction effects on optical focus, and differential thermal contraction effects on optical alignment.

This problem of temperature variations will be solved on a computer that has already been programmed by Itek thermal analysts for the solution of thermal transients in orbiting objects. As will be explained in the following paragraphs, the variation of material properties with temperature and the thermal contraction effects are considerably more problematic than lubrication.

5.1.4.2.2 Solution of Thermal Contraction Problems, with both Uniform and Non-uniform Temperature Distribution, for Optics, Structure, Bearings, and Data Components - Thermal contraction phenomena will produce mechanical stresses in most parts and structures, but this is not a serious problem since these thermally-induced stresses occur only in orbit and therefore are never superimposed on the stresses due to launching accelerations and vibrations. The most significant result of thermal contraction is its effect on optical focus, optical alignment, and data component alignment. The magnitude of the problem increases linearly with the size of the structures holding the various components. If automatic rather than manual focus compensation is required, the problem could possibly be solved by incorporating passive bimetallic compensators in the focusing mechanism. It is also possible to use double mounting, using materials of differing expansion rates such that the location of the thermal contraction nodal point can be chosen. A more difficult problem lies in maintaining optical and data component alignment. Because tracking accuracies of about 1 arc-second, and pointing accuracies of less than 1 arc-minute are required, backlash, radial and axial play, and mechanical shift cannot be tolerated. A very reliable method for solving this problem employs a jaw clutch at differential thermal contraction interfaces. The radial teeth of such a coupling can shift relative to each other in a radial direction, while rotational displacements are eliminated. Axial clamping maintains the jaws in tight contact. Jaw clutches might be used to join Invar mirror mounts to magnesium structures, and magnesium structures to steel bearing shafts. Further study will be necessary to determine if thermal and alignment problems warrant the expense of such a device.

5.1.4.2.3 Optimization of Weight and Structure Stiffness - In the attempt to minimize weight, the lower limit of system weight will be set partly by stress considerations, but mostly by stiffness requirements for optical accuracy and repeatability. The achievement of low weight will be implemented by the use of such fabrication techniques as chemical milling of magnesium castings and aluminum extrusions. Weight control will be monitored continuously.

5.1.4.2.4 Minimization of Optical Vignetting by Structural Elements - This problem is related to the foregoing because it involves the design of truss-type or space frame structures wherever optical obstructions occur (e.g. the roll arm of both scanning pedestals).

5.1.4.2.5 Designing for Launching Acceleration and Vibration - Efforts will be made to limit all mechanical stresses to the elastic limit of the

various materials used, thereby ensuring optical accuracy and repeatability. An operating model of the IVSS will be built early in the development phase and subjected to vibration and shock testing. This testing is scheduled early enough in the program to permit necessary changes to the final design.

5.1.4.2.6 Incorporation of Design Features for Reverse and Plunge Alignment Capability - Reverse and plunge capability is considered necessary for rapid and economical alignment checkout. Design considerations include mounting surfaces for accessory precision bubble levels and possibly mirrors, in addition to the capability for 180° travel about the roll and pitch axes. A detailed test procedure must be devised.

5.1.4.2.7 Optimization of Friction Torque and Noise with Stiffness (Preload) of the Roll and Pitch Bearings - The low torque, high-resolution servomechanism driving the scanning pedestals must necessarily use bearings having extremely low friction and noise. Contrarily, optical performance requires stiff, preloaded ball bearings giving negligible deflection with the change from 1-G gravitation to orbital weightlessness. Accelerations due to pedestal scanning are extremely low (about 1/30 G), therefore almost negligible. But the possiblity of a vibration environment generated by spacecraft components in orbit must be investigated. Preliminary investigations with a bearing manufacturer indicates that the largest bearing in the proposed design of the scanning pedestals (a 10-inch bore diameter, thin-section bearing) can yield a maximum friction torque of less than an initial target value of 8 ounce-inches with a light preload. The bearing would be of the four-point contact type, and would be internally preloaded. Efforts will still be made to utilize a preloaded pair because these can be preloaded with a spring. This feature automatically compensates for varying radial play caused by shrinkage of the housing around the outer race; therefore, tends to maintain nearly constant preload and nearly constant friction torque. The preloaded bearing will maintain accurate alignment if the preload is greater than the equivalent applied operating load. Bearing noise, on the other hand, is reduced by additional precision machining of the bearing races and, to some extent, of the balls. Improvement of the ball retainer will also reduce both friction torque and noise.

5.1.4.2.8 Choosing of Materials and Fabrication Processes - Special consideration must be given to materials and fabrication processes because of the unique environments imposed by space. Extremely low temperatures cause many precipitation-hardening metals, such as aluminum alloys and martensitic steels, to pass through a transition stage into a highly brittle range. The effect is not so noticeable in austenitic steels such as the 300-series stainless steels.

Consideration of embrittlement extends especially to castings and weldments, where stress raisers caused by porosity, shrinkage, non-homogeneous inclusions and other defects can combine with material embrittlement to cause catastrophic failure. Even though environmental loads during orbit are apparently negligible, some problem of embrittlement remains because of various stresses induced by clamping, bolting, and by differential thermal contraction.

5.1.4.2.9 Optimizing Compliance, Stress, and Volume in the Flexing Electrical Cables — Flexible loops or coils of cables, rather than slip rings, will be used to carry electrical power and signals across the roll axes of both high and low power scanning pedestals. Low stress and low compliance (low resistance to motor torque) go hand-in-hand, but these two variables are traded off with volume of the loop package. The pitch axes do not transport any electrical power or signals.

5.1.4.2.10 Elimination of Lubrication as a Problem in a Space Environment — Originally one of the most difficult of design problems, lubrication in space at extremely low temperatures and pressures has been successfully achieved with several now-standard solutions. Sliding friction and wear are reduced to satisfactory limits using the patented Ball Brother Process on such surfaces as slip rings, motor commutators and brushes. Ball bearing lubrication has been very successfully accomplished using solid lubricant particles rubbed off the ball retainer by the balls and deposited on the raceways. Running-in of the bearing preconditions the bearing by depositing the particles on the raceways before the bearing is assembled into the equipment. This design has been successfully applied by the Barden Corporation with their "Bartemp" bearing, consisting of 440C stainless steel balls and races with a teflon retainer impregnated with molybdenum disulfide and glass fibers. The Kaydon Engineering Corporation uses a solid teflon retainer and also achieves successful results in space environments.

5.2 Preliminary Requirements for the IVSS Aerospace Ground Equipment (AGE)

The requirements for IVSS AGE may be divided into the following three categories: (1) the equipment required at the vendor's plant to permit the rational fabrication and testing of major subassemblies, (2) the equipment needed at both the vendor's plant and at any field site where major and minor subassemblies of the IVSS may be tested, and (3) specialized equipment for clocking out the IVSS system immediately prior to launch.

The first category includes the seismically isolated environmental test chambers necessary for checkout of the pointing and tracking telescope, system's retention of angular acuity during at least a 30-day cycle of orbital vacuum and thermal simulations. Associated with these chambers is a similarly well isolated test target generator, including a collimator and moving target generator. The latter equipment will also allow check-out of the servo system and its associated electronics. For these tests, which also form part of a quality assurance and control program, the vendor must also have a mock-up of a significant portion of the spacecraft structure. The PTS will be coupled to this structure by a critically important vacuum seal.

In the second category are such devices as a dolly for instrument transport and shop assembly, a variety of test input generators, and electronic analysis equipment. Dollys and their lifting rigs should be carefully designed to minimize distortion and flexing of the PTS support structure during handling operations. Such handling equipment will be required at both the vendor's plant and at each site where an IVSS system is installed and/or dismantled.

There are two classes of test generators and analysis equipment. It is assumed that over-all IVSS performance will be tested at field sites through use of large-scale, integrated, automatic system check-out and test facilities. Such automatic check-out may necessitate tie-in to a large computer for accuracy checks and malfunction detection. On the other hand, expedient assembly testing and checking out of subassemblies will be aided by the provision of a variety of independent test signal generators and analysis equipment. Typical of these units, which are planned for use at both the vendor's plant and at deployment sites, are focus signal generators, derotation signal generators, dummy operator signal generators (magnification change,), camera cycle control signal generators, servo input signal generators, oscilloscopes, and voltmeters.

The third category of AGE includes the equipment specifically fabricated for go/no-go testing of the entire IVSS system. Because of the specialized nature of these tests, this equipment, unlike that in the other two categories, must be designed and built specifically for these pre-launch tests.

5.3 Ground Support System

5.3.1 Requirements Summary

5.3.1.1 Tracking

Ephemeris data accuracy will determine the necessary tracking accuracy and frequency. A detailed analysis of ephemeris accuracy as applicable to the IVSS will be performed during the next phase, but for this report the accuracy achievable with the network shown in Figure 5-6 is assumed to be satisfactory.

5.3.1.2 Telemetry

Based on number of experiments performed and data accumulated, the following data will be transmitted daily to the ground support network.

Normal Data: 1550 bits $\times$ 3600 seconds = 5.58×10^6 bits/day

Photo Tag Data: 260 bits $\times$ 1000 photos = 0.26×10^6 bits/day

Photo Interpretation Data: 80 bits $\times$ 30 frames = 0.0024×10^6 bits/day

Alignment and Calibration: 72,034 bits $\times$ 20 seconds = 1.4407×10^6 bits/day

Total: 7.3×10^6 bits/day

Allowing a safety factor of approximately 25 percent, the total data storage and transmission requirements for all IVSS data will be approximately 9 million bits per day.

5.3.1.3 Command

The amount and type of data which must be sent to the vehicle for IVSS experiment performance will be determined in the next phase of the IVSS study. For purposes of this analysis, IBM assumes that two ZI stations equipped with Gemini DCS equipment will satisfy this requirement.

5.3.1.4 Voice

No firm real-time voice requirement is postulated for IVSS, but the capability will be available in the ground support network if further studies show it necessary.

5.3.1.5 Control

An experimental control point for IVSS can be established if study indicates a need. This ground support plan will not show one, but it can be incorporated any place with adequate communications links to the Mission Control Center for MOL.

5.3.1.6 Targets

It is assumed that all ground target needs can be met by one of the 55 targets shown in Table 5-11. Additional study and definition during the next phase of IVSS will determine the specific targets to be used and what preparation will be required.

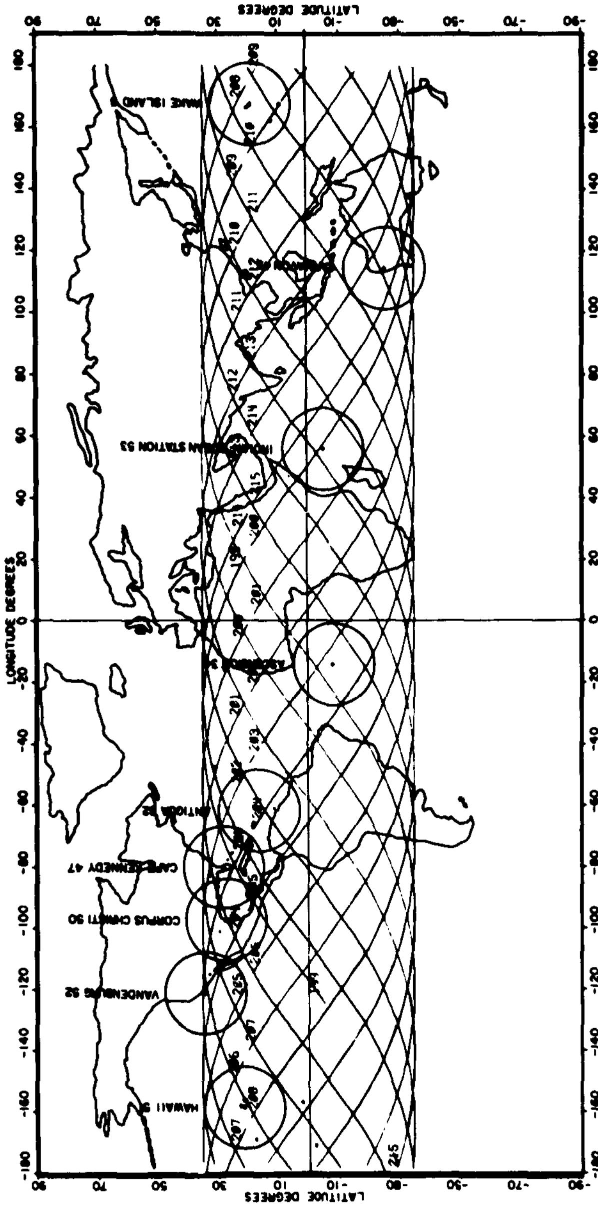


Figure 5-6. Ground Support Network and Coverage On Typical Day

Table 5-11.

IVSS TARGET CHARACTERISTICS

Name	Latitude	Longitude	Possible Targets
Dow AFB	44°48'	68°50'	B-52 A/C
Plattsburg AFB	44°41'30"	73°32'	Atlas F
Wurtsmith AFB	44°28'	83°27'	B-52 A/C
Ellsworth AFB	44°8'30"	103°6'	B-52 A/C Minuteman Titan I
Griffiss AFB	43°15'	75°25'	B-52 A/C
Mountain Home AFB	43°3'	115°52'	Titan I
Westover AFB	42°12'	72°32'	B-52 A/C 8th AF Hq.
Warren AFB	41°9'30"	104°48'	Minuteman Atlas D. E.
Offutt	41°8'30"	95°55'	SAC Hq. Atlas D
Hill AFB	41°7'	111°58'30"	Depot
Lincoln AFB	40°50'	96°48'	Atlas F
Bunker Hill AFB	40°38'	86°10'	B-58 A/C
Wright Patterson AFB	39°46'30"	84°6'	B-52 A/C AFSC AFLC
Lowry AFB	39°41'30"	104°53'	Titan I AF Training Center
Beale AFB	39°7'	121°34'	Titan I B-52 A/C
Forbes AFB	38°56'30"	95°40'	Atlas E
Schilling AFB	38°47'	97°38'	Atlas F
Mather AFB	38°34'	121°17'	B-52 A/C AF Training Center
Whiteman AFB	38°33'	93°33'	Minuteman
Travis AFB	38°14'	121°57'	B-52 A/C Military Air Transportation
McConnell AFB	37°37'30"	97°16"	Titan II The Boeing Co. Wichita

Table 5-11.

IVSS Target Characteristics (cont)

Name	Latitude	Longitude	Possible Targets
Castle AFB	37°23'	120°32'30"	B-52 A/C
Norfolk	36°54'	76°58'	Shipyard
Blytheville AFB	35°57'30"	89°56'30"	B-52 A/C
Tinker AFB	35°25'	97°23'30"	AF Depot Oklahoma City
Clinton Sherman AFB	35°2' 30"	99°12'	B-52 A/C
Seymour Johnson AFB	35°20'30"	77°58'	B-52 A/C
Amarillo AFB	35°13'30"	101°42'	B-52 A/C
Little Rock AFB	34°55'30"	92°9'	Titan II
Edwards AFB	34°54'	117°53'	AF Test Range a- Sighting from Space b- Sighting from Ground (Tracking Capabilities)
Vandenberg AFB	34°42'	120°33'	Atlas D. E. F. Various Facilities for Missile & Space Vehicle Launches Tracking Capabilities
Altus AFB	34°39'	99°16'30"	B-52 A/C Atlas F
Sheppard AFB	33°59'	98°30'30"	B-52 A/C
March AFB	33°53'	117°16"	B-52 A/C 15th AF Hq.
Columbus AFB	33°37'38"	88°26'	B-52 A/C
Walker AFB	33°18'	104°31'	B-52 A/C Atlas F
Holloman AFB	32°52'	106°6'	WSMR a- Sight from Space b- Tracking Capabilities
Carswell AFB	32°46'30"	97°26'	B-58 A/C B-52 A/C Dallas, Ft. Worth
Warner Robbins AFB	32°38'	82°35'	B-52 A/C Depot, Electronics
Yuma Test Range	32°38'	114°35'	Test Range a- Sight from Space

Table 5-11.

IVSS Target Characteristics (cont)

	Latitude	Longitude	
Barksdale AFB	32°30'	93°39'30"	B-52 A/C 2nd AF Hq.
Dyess AFB	32°25'30'	99°51'	B-52 A/C Atlas F
Davis-Monthan AFB	32°7'	110°50'	Titan II
Biggs AFB	31°50'	106°23'30"	B-52 A/C
Turner AFB	31°36'	84°7'	B-52 A/C
Eglin AFB	30°29'	86°30"	Test Range (AFSC) a- Sight from Space b- Tracking Capabilities B-52 A/C
Bergstron AFB	30°13'	97°41'	B-52 A/C
Laughlin AFB	29°23'	100°47'	AF ECM Center
Cape Kennedy AMR	28°28'	80°33'	Atlantic Missile Range a- Sight from Space b- Tracking Capabilities
McCoy AFB	28°27'	81°19"	B-52 A/C
McDill AFB	27°51"	82°31'30"	B-52 A/C
Homestead AFB	25°29'	80°24'	B-52 A/C Miami a- City Complex b- (?) Visual Space Sighting Range
Bellow AFB	21°21'	157°43'30'	Ocean Targets Terrain Targets Equipment Checkpoint
Hickam AFB	21°19'30"	157°58'	Military Air Transport Terrain Target
Ramey AFB	18°29'	67°9'	B-52 A/C Ocean Target

5.3.2 Support Plan

To support the preceding requirements, the following configuration is recommended:

5.3.2.1 Tracking

Cape Kennedy	"C"-Band Radar
Antigua	"C"-Band Radar
Ascension	"C"-Band Radar
I.O.S.	"S"-Band Radar
Carnarvon	"C"-Band Radar
Wake	Shipborne "C"-Band Radar
Vandenberg	"S"-Band Radar
Corpus Christi	"S"-Band Radar

Figure 5-6 shows a typical day's ground track of the MOL at 165 n mi altitude and an inclination of 35 degrees. The selected station coverages for 5 degrees elevation are shown.

5.3.2.2 Telemetry

To support the telemetry requirements, the same ground support network of Figure 5-6 will be utilized. This network supplies approximately 340 minutes of coverage per day. At the required daily rate of 9 megabits, this averages out to a telemetry rate of 4.5 kilobits per second, which is well within the capability of the selected stations whose configurations are shown in Table 5-12.

5.3.2.3 Command

It is assumed that all necessary commands to the IVSS experimenters can be relayed via the Digital Command Systems at Corpus Christi and Cape Kennedy. These two stations afford approximately 78 minutes per day of digital command capability. Their coverage is shown in Figure 5-6.

5.3.2.4 Voice

Voice contact can be made from all the stations indicated in Figure 5-6 and with many of the targets that may be utilized for IVSS.

5.3.2.5 Control

Additional study during the next phase of IVSS will detail the ground operational philosophy of the experiment. At present no real time control is indicated, hence the use of space in the MOL Mission Control Center will be minimal with most of the data being processed after the experiment at some selected facility. Data will be hand-carried from the MCC, which will be the focal point for all collected data in MOL.

Table 5-12.

GROUND STATION INSTRUMENTATION CAPABILITY

STATION ABBREVIATION	KEN	QUI	GBI	LIM	BLO	ELU	WLP	DIX	SSI	NHS	GTI	SAN	TTS	PRI	BDA	ANT	TRI	STJ	CVI	ASC	FLY	KNO	JOH	PRE	IOS	CRO	MUO
NETWORK	MSFN	STADAN	AMR	STADAN	STADAN	AMR	STADAN		AMR	SCF	AMR	STADAN	SCF	AMR	MSFN	AMR	AMR	STADAN	MSFN	AMR	BMEWS	MSFN	STADAN	AMR	SCF	MSFN	STADAN
GOVERNMENT MANAGEMENT	NASA	NASA	USAF	NASA	NASA	USAF	NASA	US ARMY	USAF	USAF	USAF	NASA	USAF	USAF	NASA	USAF	USAF	NASA	NASA	USAF	USAF	NASA	NASA	USAF	USAF	NASA	NASA
LOCATION	CAPE KENNEDY, FLORIDA	QUITO, EQUADOR	GRAND BAHAMA ISLAND, B.W.I.	LIMA PERU	BLOSSOM POINT MARYLAND	ELEUTHERA ISLAND B.W.I.	WALLOPS ISLAND VIRGINIA	FORT DIX, NEW JERSEY	SAN SALVADOR ISLAND B.W.I.	NEW HAMPSHIRE STATION	GRAND TURK ISLAND B.W.I.	SANTIAGO, CHILE	TULE TEST STATION GREENLAND	PUERTO RICO	BERMUDA	ANTIQUA ISLAND B.W.I.	TRINIDAD ISLAND, B.W.I.	SAINT JOHNS, NEWFOUNDLAND	GRAND CANARY ISLAND	ASCENSION ISLAND	FLYINGDALE MOOR, ENGLAND	KANO NIGERIA	JOHANNESBURG SOUTH AFRICA	PRETORIA, SOUTH AFRICA	INDIAN OCEAN STATION	CARNARVON AUSTRALIA	MUCHEA, AUSTRALIA

		GROUND STATION	KEN	QUI	GBI	LIM	BLO	ELU	WLP	DIX	SSI	NHS	GTI	SAN	TTS	PRI	BDA	ANT	TRI	STJ	CVI	ASC	FLY	KNO	JOH	PRE	IOS	CRO	MUO	D
INSTRUMENTATION	ON-SITE DATA PROCESSOR	FACILITY	G									F			F	O	G	O			G						F	G		
		TYPE	[illegible] 7094									CDC 160-A			CDC 160-A	CDC 160-A	TRW 130	RCA 4101									CDC 160 A			
	VOICE COMMUNICATION	VHF	OG		O				G		G						G	OG			G	O		G		O		G	G	
		S-BAND	A						A			D			D		A				A						D	A		
		HF	G		O				G		G						G	OG			G	O		G		O		G	G	
	FM FM TELEMETRY	X-BAND							G								G													
		S-BAND	A						A			FD			FD		A				A						FD	A		
		UHF			O							F			F							O				O	F			
		VHF	OG	O	O	O	O		G		O	F	O	O	F		OG	O		O	G	O		G	O	O	F	G	G	
	PCM TELEMETRY	X-BAND							G								G													
		S-BAND	A						A			FD			D		A				A						FD	A		
		UHF										F															F			
		VHF	G	O	O	O	O		G			F		O			G			O	G				O		F	G		
	COMMAND AND CONTROL	DIGITAL	GA		O				GA		O	FD	O		D		GA				GA						D	GA		
		TONE	G		O				G		OG	F	O		F		G	G			G						F	G		
	RADAR TRACKING	X-BAND																												
		C-BAND	G		O				G		O		O			O	G	O				O				O		G		
		S BAND	G		O			O	G		O	FD	O		FD		GA	O			G						FD	A	G	

MSFN - MANNED SPACE FLIGHT NETWORK
STADAN - SPACE TRACKING & DATA ACQUISITION NETWORK
AMR - ATLANTIC MISSILE RANGE
SCF - SATELLITE CONTROL FACILITY
BMEWS - BALLISTIC MISSILE EARLY WARNING SYSTEM

DSIF DEEP SPACE INSTRUMENTATION FACILITY
PMR - PACIFIC MISSILE RANGE
SPASUR SPACE SURVEILLANCE NETWORK
EGTR EGLIN GULF TEST RANGE

KE

7

JOH	PRE	IOS	CRO	MUO	DAR	WOM	ENI	WAI	KWP	MID	CTN	JSN	TER	HTS	CHR	KTS	CLR	COL	ROB	CAL	VTS	EDW	DGO	GOL	YUM	GYM	HUA	ELE	WHS	TEX	EGF	SIL	EFL	JOR	CSB	ROS	ANC	MAR	STE	CUD
STADAN	AMR	SCF	MSFN	STADAN	STADAN	DSIF	PMR	PMR	PMR	PMR	PMR	PMR	PMR	SCF	PMR	SCF	BMEWS	STADAN		PMR	SCF		SPASUR	DSIF		MSFN		SPASUR	MSFN	MSFN	STADAN	SPASUR	MSFN	SPASUR	EGTR	STADAN	EGTR	EGTR	SPASUR	EGTR
NASA	USAF	USAF	NASA	NASA	NASA	NASA	USAF	UASF	USAF	USAF	USAF	USAF	USAF	USAF	USAF	USAF	USAF	NASA	US ARMY	USAF	USAF	USAF	US NAVY	NASA	US ARMY	NASA	US ARMY	US NAVY	NASA	NASA	NASA	US NAVY	NASA	US NAVY	USAF	NASA	USAF	USAF	US NAVY	USAF
JOHANNESBURG SOUTH AFRICA	PRETORIA SOUTH AFRICA	INDIAN OCEAN STATION	CARNARVON AUSTRALIA	MUCHEA, AUSTRALIA	DARWIN, AUSTRALIA	WOOMERA AUSTRALIA	ENIWETOK ISLAND PACIFIC	WAKE ISLAND PACIFIC	KWAJALEIN ISLAND PACIFIC	MIDWAY ISLAND, PACIFIC	CANTON ISLAND PACIFIC	JOHNSON ISLAND PACIFIC	TERN ISLAND PACIFIC	HAWAII TEST STATION	CHRISTMAS ISLAND, PACIFIC	KADIAK TEST STATION	CLEAR ALASKA	COLLEGE ALASKA	CAMP ROBERTS CALIFORNIA	PT ARGUELLO CALIFORNIA	VANDENBERG TEST STATION	EDWARDS AFB, CALIFORNIA	SAN DIEGO CALIFORNIA	GOLDSTONE, CALIFORNIA	YUMA, ARIZONA	GUAYMOS, MEXICO	FORT HUACHUCA, ARIZONA	ELEPHANT BUTTE, NEW MEXICO	WHITE SANDS, NEW MEXICO	CORPUS CHRISTIE, TEXAS	EAST GRAND FORK, MINNESOTA	SILVER LAKE, MISSISSIPPI	EGLIN AFB FLORIDA	JORDAN LAKE, ALABAMA	CAPE SAN BLAS, FLORIDA	ROSSMAN, NORTH CAROLINA	ANCLOTE POINT, FLORIDA	MARCO ISLAND, FLORIDA	FORT STEWART, GEORGIA	CUDJOE KEY, FLORIDA

JOH	PRE	IOS	CRO	MUO	DAR	WOM	ENI	WAI	KWA	MID	CTN	JSN	TER	HTS	CHR	KTS	CLR	COL	ROB	CAL	VTS	EDW	DGO	GOL	YUM	GYM	HUA	ELE	WHS	TEX	EGF	SIL	EGL	JOR	CSB	ROS	ANC	MAR	STE	CUD
		F	G						0			0		F		F				0	F	0	0			G			G	G			G			0				
		CDC 160 A							7090					CDC 160-A		CDC 160-A				7090	CDC 160-A	7094	7090						7090				7094			PB 250				
	0		G	G							G									G						G				G										
		D	A											D		D					D					A				A										
	0		G	G							G									G						G				G										
		FD	A											FD		FD					FD					A				A										
	0	F			0	0								F		F					F			0																
0	0	F	G	G	0	0			0		0	0		F	0	F		0			F		0	0		G			0	G	0		G		0		0	0		0
		FD	A											FD		D					FD					A				A										
		F			0									F							F																			
0		F	G		0									F				0			F					G				G	0		G		0					
		D	GA		0									D		D		0			FD									G	0									
		F	G		0	0								F		F		0		G	F					GA				GA	0						0	0		0
							0		0										0	0			0																	
	0		G			0						0							0	G		0					0		G				G		0		0	0		
		FD	A	G					0					FD		FD				G	FD			0		G				G			G		0	0		0		0

KEY. A NASA FACILITY (APOLLO) UNIFIED S BAND SYSTEM
G NASA FACILITY (GEMINI) MANNED SPACE FLIGHT NETWORK
D DEPARTMENT OF DEFENSE FACILITY SPACE TO GROUND LINK SYSTEM
F DEPARTMENT OF DEFENSE FACILITY SATELLITE CONTROL
0 OTHER FACILITY

*WRED AC DIGITAL COMPUTER
**SPERRY RAND USQ-20

2

5.3.2.6 Targets

A list of possible targets is shown in Table 5-11. In addition, Figure 5-7 shows 11 of these targets with the 300 n mi radius circle indicating the viewing time for the IVSS experiment when MOL vehicle is at 165 n mi. These coverages assume a 60 degree cone of view from the vehicle. The larger circles are the viewing time of the ground support network selected. Figure 5-8 shows a representative day of orbits of the MOL superimposed on the target view times to show when the targets are in view during an orbit. In addition, Figure 5-9 is a composite showing the MOL ground support network coverage, the IVSS target view times, one representative day of ground tracks and the world map.

Table 5-12 shows the space-to-ground-link station instrumentation availability at various geographical locations. It can be utilized in planning the IVSS experiment.

5.3.3 <u>Ground Support Assistance in In-flight Malfunction Detection and Remidial Action</u>

To effectively utilize available experiment time aboard the MOL, it is necessary to perform a detailed study of the Ground Support Systems capability to assist in on-board equipment malfunction analysis and repair. The time at which the astronaut and/or ground system detect a malfunction depends on two factors:

- Scheduled equipment check-outs by the experimenters.
- Scheduled equipment check-out by the ground support system based on telemetered data.

The capability of each of the above depends on the vehicle equipment design, operational philosophy, and ground support systems design. For example, the vehicle equipment design may incorporate sufficient sensors to telemeter enough information for ground support personnel to detect malfunctions in sufficient time to effect many repairs that would prevent experiment performance. The experiment operational philosophy may call for periodic check-out of the experimental equipment to allow adequate time for repair prior to experiment performance. The ground support system may call for extensive contact coverage with the vehicle to minimize the time between malfunction detection and instruction for repair procedures.

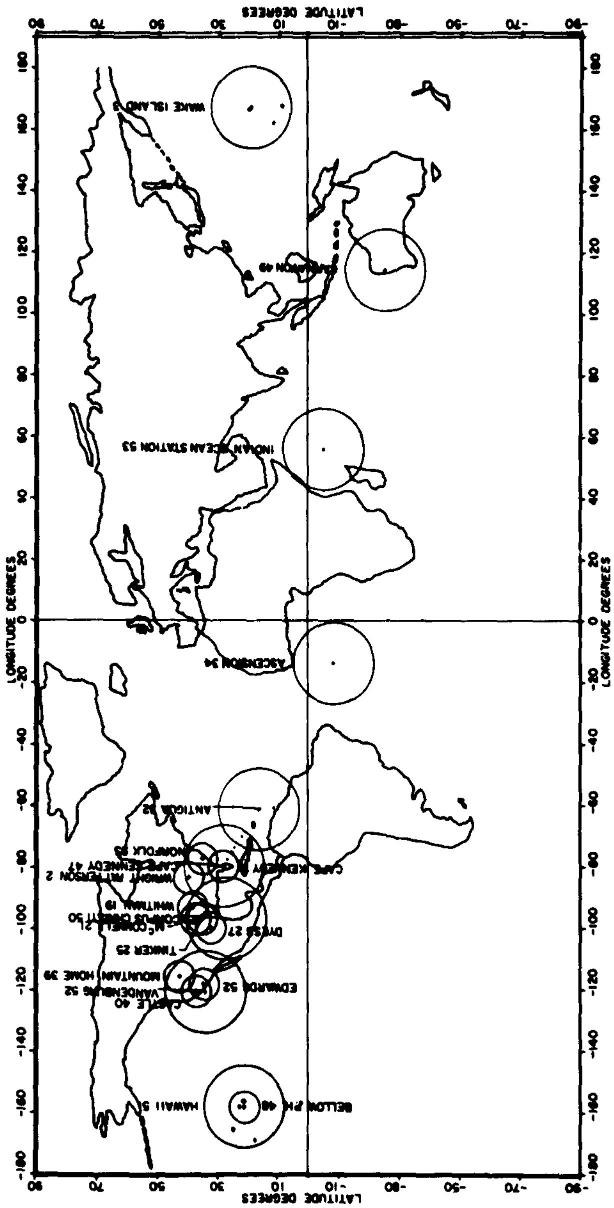


Figure 5-7. Selected Targets and Viewing Times

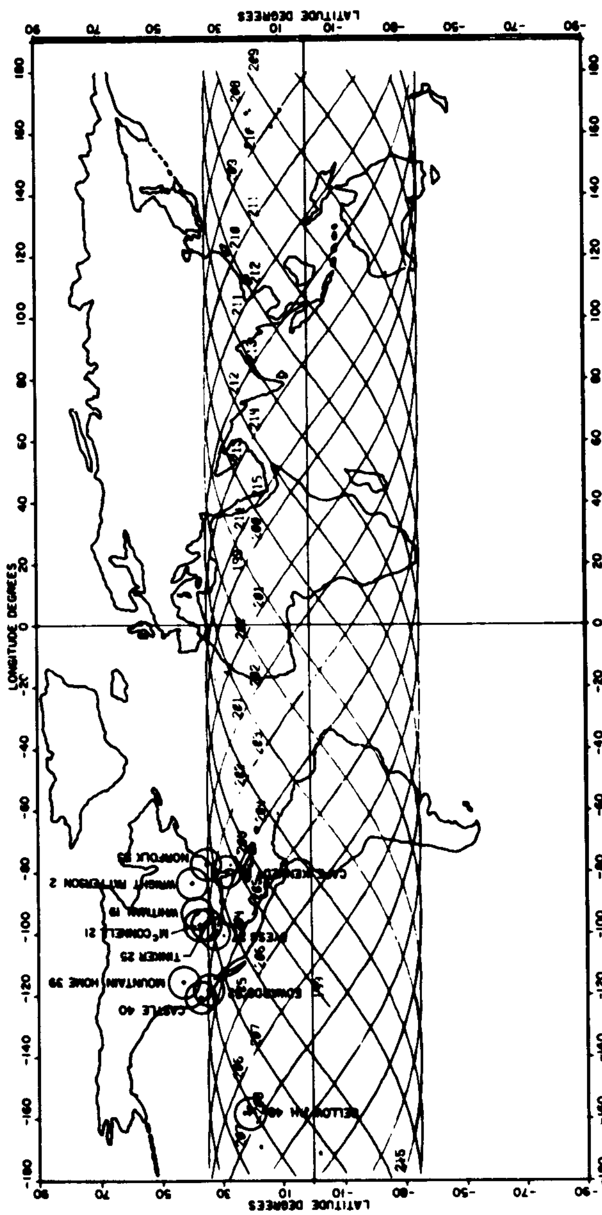


Figure 5-8. Representative Day of Orbits and Target Viewing Times

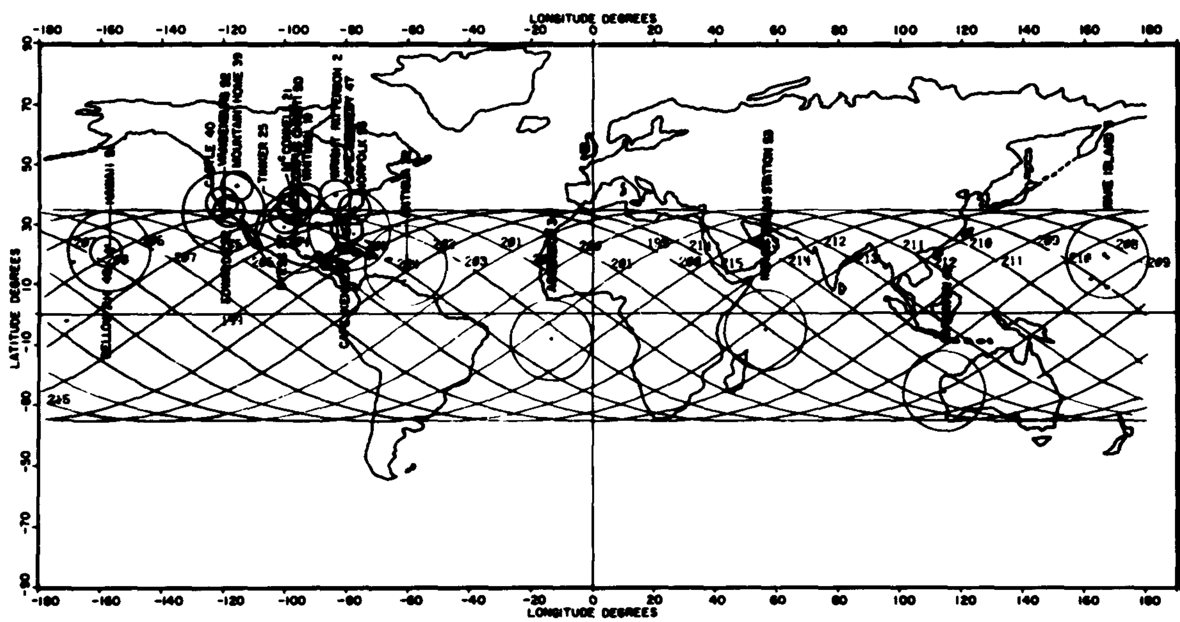


Figure 5-9. Composite of Ground Networks, Target Viewing Times, Ground Tracks, and World Map

Figure 5-10 illustrates some of the possibilities and indicates areas requiring analysis. For example, referring to Figure 5-10, the following comments apply:

	Block No.	Comment
•	1 to 2 or 4	Depends on degree of automation and number of checks required to verify equipment.
•	5	Performed if astronaut decides he can or must, (ditto Block 6).
•	6	The amount of data required depends on the type of malfunction.

This analysis assumes that the ground support system consists of:

- Sufficient network sites to obtain the telemetered data required.
- The communications needed to transmit required data from network sites to the Mission Control Center.
- An exact duplicate of the vehicle in the MCC to simulate the malfunction and check the repair procedure.
- Availability of top engineers in the simulation facility.
- Operational philosophy and experiment schedule that allows flexibility to work around stubborn malfunctions.

5.3.4 Processing of Telemetered Data

During subsequent phases of the IVSS Program, the data processing requirements will be analyzed. Preliminary analysis reveals the type of data to be processed and the information to be outputed are similar to those of other Air Force Programs. IBM will investigate existing data processing systems for similar programs and will use this information in the IVSS Program.

At present, IBM has a subcontract with the Lockheed Aircraft Company, Sunnyvale, California, which is concerned with data processing in the area of programming. This and other programs will be evaluated for useful information to apply in the IVSS Program upon establishment of necessary "need to know" clearances.

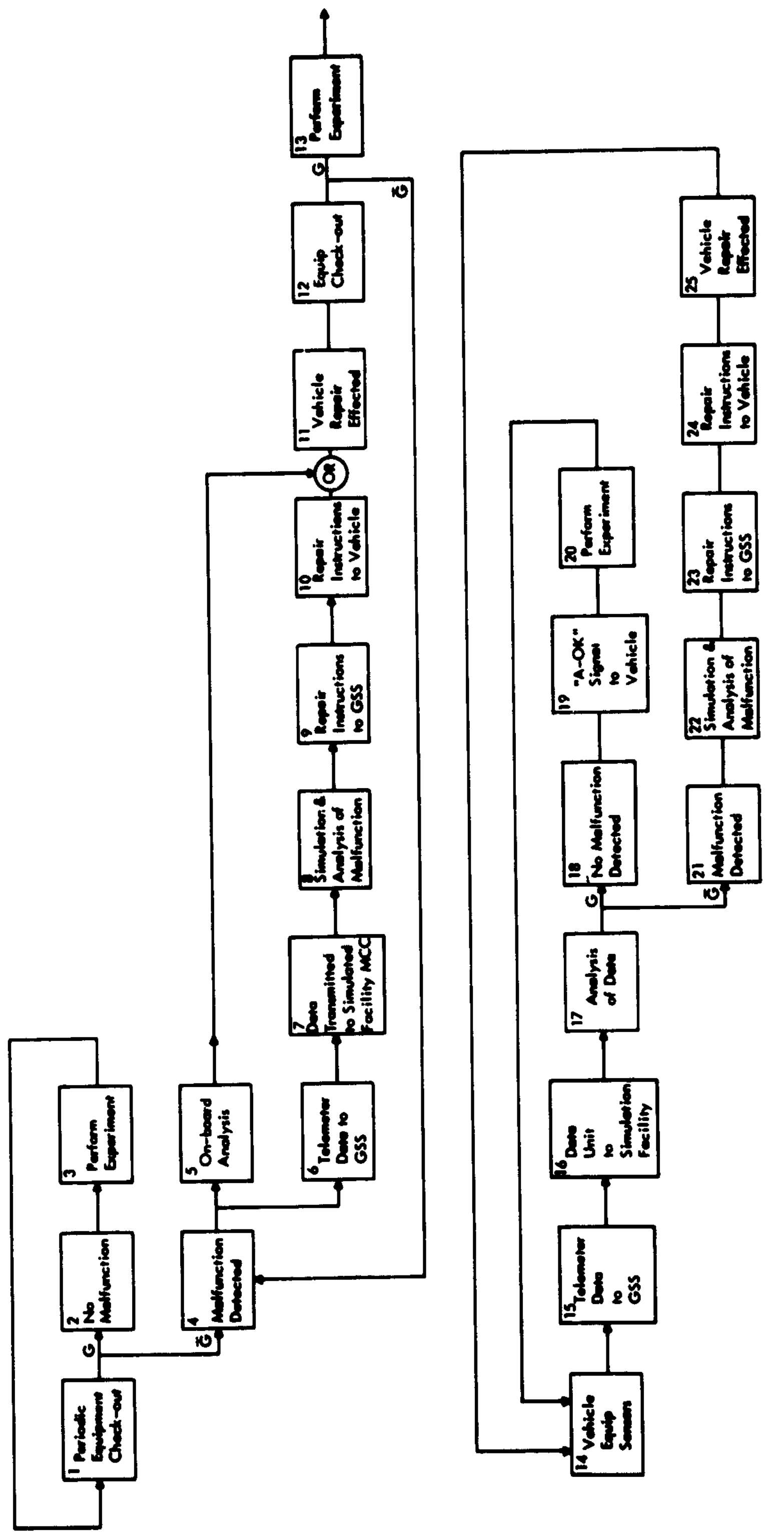


Figure 5-10. Functional Flow Chart—Malfunction Detection and Remedial Action
(In Flight and Ground Support)

5.4 Vehicle Interface Requirements

This section is to present requirements of the IVSS interface with the MOL equipment consisting of the following:

- The attitude reference, stabilization, and control system requirements
- Central computer requirements
- Data management requirements
- Communication requirements
- Environmental control requirements
- Vehicle installation requirements

The above listed requirements are described separately in the following sections. Presented therein are the requirements only, the trade off and synthesis efforts necessary to arrive at these requirements are described in Sections 3 and 4 respectively.

5.4.1 Attitude Reference Stabilization Control Requirements

Table 5-13 contains the interface requirements for the MOL attitude reference, stabilization control sensors (which include the rate gyros and/or the rate integrating gyros), horizon sensors, and the attitude control system. The environmental specifications for these sensors are contained in Table 5-25 plus Figure 5-14 and 5-15. These environmental specifications are based on the Titan III vibration acceleration profiles.

5.4.2 Central Computer Requirements

Table 5-14 shows the significant digital computer requirements for the two modes of operation discussed in Section 4.2. The primary mode is the minimum digital approach while extended capability includes the data filtering and ephemeris updates and several of the other computations required to go from one target to another in an open loop fashion. Figure 5-11 includes the computational requirements for the extended capability and primary modes of operations. The total instruction storage is shown in Table 5-14 along with the longest loop instructions and the required solution rates for each of the major computational blocks. The equations associated with these major computational blocks are presented in Section 4.2.

Table 5-13
IVSS INTERFACE REQUIREMENTS FOR MOL ATTITUDE REFERENCE, AND STABILIZATION CONTROL SENSORS

Requirements Imposed by IVSS	MOL ATTITUDE REFERENCE, STABILIZATION AND CONTROL SENSORS			
	Attitude Control	Rate Gyros	Rate Integrating Gyros	Horizon Sensors
(1) Function:				
a. Tracking	Null Vehicle Rates, then Shut Down after Acquisition. Limit Cycle $\pm 3^{o}$ $\pm 0.01^{o}$/Sec	Supply Body Axis Rates to Computer	—	—
b. Not Tracking	Keeps Vehicle X Axis along Vel. Vector $\pm 3^{o}$ to 4^{o}	Used to Null Vehicle Rates Prior to Tracking	Used in Gyro Compassing Mode to Adjust Yaw Attitude	Used to Keep Pitch and Roll Axis in the Horizontal Plane
(2) Field of View or Range	All Attitude 3 Axis	15^{o}/Sec	Gimbal Freedom $\pm 10^{o}$	Horizontal $\pm 80^{o}$ Vertical $\pm 4^{o}$
(3) Structural Impact	Alignment to Horizon Sensors Rate Gyros and Rate Integrating Gyros ±30 min (3σ) Attitude Control System Rotation Actuators Parallel to Vehicle Axis $\pm 1^{o}$ (3σ)	Alignment to PTS Base Plate ±45 min (3σ)	Alignment to Horizon Sensors and Attitude Control System ±30 min (3σ)	Alignment to Attitude Control System and Rate Integrating Gyros ± 30 min (3σ) Mounted on Vehicle Belly
(4) Performance				
a. Threshold	$0.05^{o}/Sec^{2}$ 0.01^{o}/Sec 0.5^{o}	0.01^{o}/Sec Max.	0.02^{o}/Hr Vertical Drift 0.03^{o}/Hr Azimuth Drift	Determine Local Vertical Within 0.1^{o} to 0.5^{o}
b. Maximum	Slew 15^{o}/Sec, $0.2^{o}/Sec^{2}$ Possible in Space Target Tracking	—	Torquing Rate $100,000^{o}$/hr	—
c. Linearity	—	0.5% at Rates of 0.05^{o}/Sec to 7.5^{o}/Sec 1.5% at Rates of 7.5^{o}/Sec to 15^{o}/Sec	0.05% of Max at Null	—

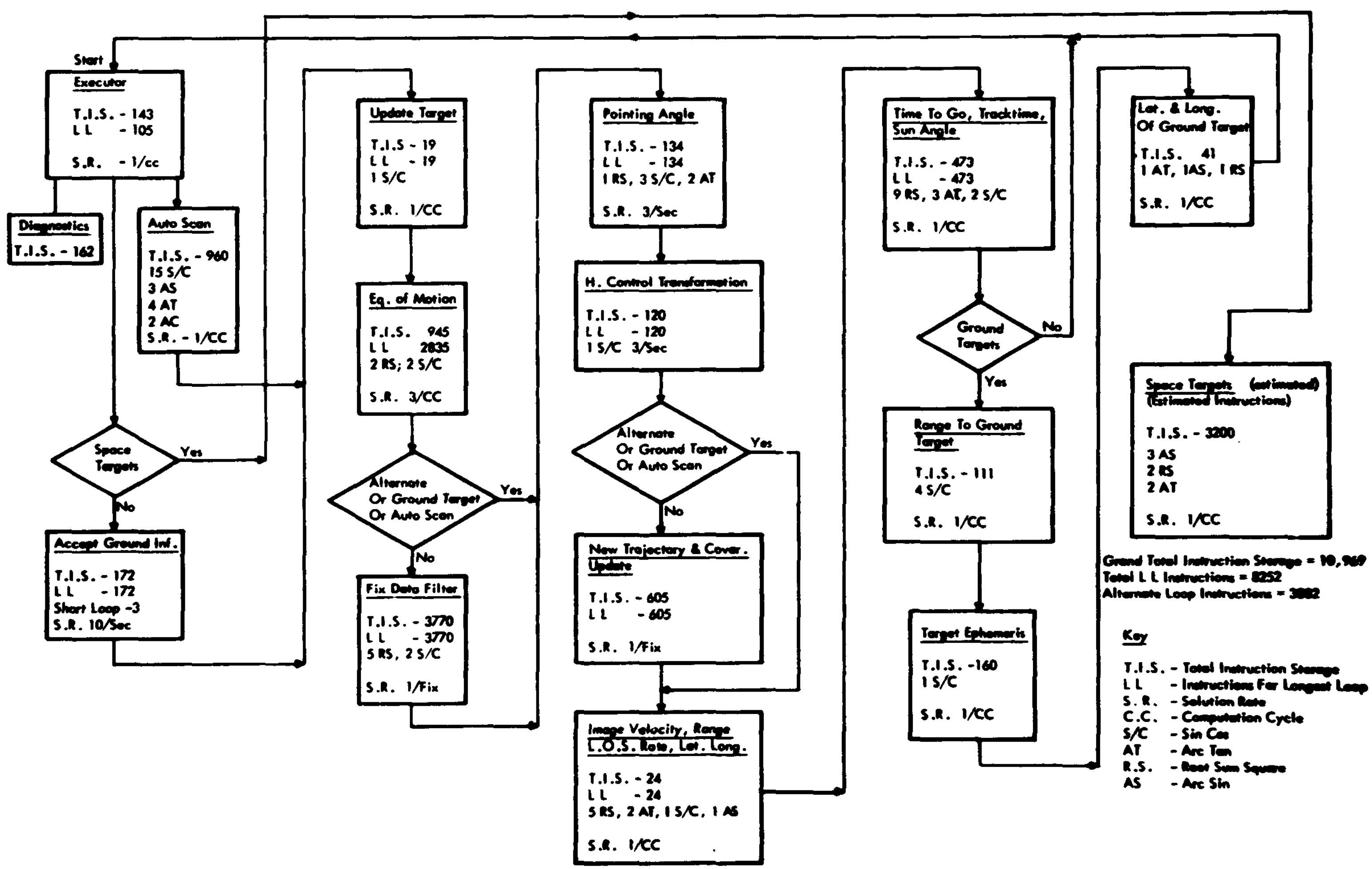


Figure 5-11. IVSS Extended Capability Digital Math Flow Requirements for P-1, P-2, and P-3

Table 5-14
DIGITAL COMPUTER REQUIREMENTS

Requirements	Primary (words)	Extended Capabilities (words)	Remarks
Total Instruction Storage *			
P-1 only	6000	12,600	Preassigned IMC evaluation
P-2 only	6300	8350	Space Target Tracking
P-3 only	7700	7700	Target of Opportunity
P-1, P-2, and P-3	12,400	18,970	
Word Size	26 Bits	26 Bits	
Solution Times	1/comp cycle to 3/sec	1/comp cycle to 3/sec	
Largest Comp Cycle	1 sec	2 sec	

* This includes provision for:

(1) Constants and variables

(2) Scaling

(3) Subroutines

5.4.3 Data Management Requirements

5.4.3.1 Data to be Sampled and Sampling Rate

The data to be sampled during an IVSS experiment have been broken into several broad categories, including:

- Console
- Sensor
- DCS-Computer Interface
- Unique Calibration Equipment

Some of the sample data from the console which is employed for real time experiment control is not recorded. This is also true of some DCS computer data. By specifying the data parameters, including their sample rates, an assessment can be made of the required bit capacity of the system.

Tables 5-15 through 5-18, at the end of this section, list the data in the preceding categories which impact the data acquisition system. For the sake of continuity, all console parameters are listed. In cases where no sampling or recording is necessary, it is so noted in the tables.

Table 5-15.

CONSOLE DATA REQUIREMENTS

Parameter	Purpose	Source	From	To	Type	A/D or D/A	Range of Data	Accuracy (percent)	Sample Rate	Data Bits	Remarks
CAMERA: Exposure Time	Set Camera for Different Exposure Times	Servo-Driven Tapes	IVSS Console	Computer	Analog	A/D (10 Bit)	0-5 Volts	0.1	1/sec	10 bits/sec	Perhaps Galvanometer Indicator is Adequate (2-3%) (7 Bits)
Exposure Select	Select Mode of Exposure Control	Discrete Rotary Dial (3 Positions)	Console	Computer	3 Dis-crete(s)	No		N/A	1/sec	3 bits/sec	
Frames Remaining	Indicate End of Film or if Magazine Should Be Reloaded	Insert/Display Rotary Decimal Thumb-Wheels	Camera	Console	Digital	No		N/A	Once per Interrupt for Film Ident. Data	Est. Average 12 Bits/ 10 Sec	3 Wheels, 4 Binary Bits/ Wheel
Film Type Annunciator	Identify Film Type Being Used in Test	Push-Button Lights (5)	IVSS Console	Computer	5 Dis-crete(s)	No		N/A	1/Min	5 Bits/ Min	
Frame Rate	Select No. of Pictures per Second or Man/ Prog. Select	Discrete Rotary Dial (16 Positions)	Console	Computer	16 Dis-crete(s)	No		N/A	1/Sec	16 Bits/ Sec	
Filter Select	Self-Evident	Discrete Rotary Dial (6 Positions)	Console	Computer	6 Dis-crete(s)	No		N/A	1/10 Sec	6 Bits/ 10 Sec	
BRIEFING PANEL: Display Mode	Selects "On-Off" of Briefing Slide-Data	2-Position Rotary Switch	Console	Computer	2 Dis-crete(s)	No		N/A	1/Sec	1 Bits/Sec	
Brief Intensity	Self-Evident	"Pot" Rotary	Console	Briefing Optical Sub-system Light	Analog	No	← Does not Require Sampling or Recording →				
Slide Orientation	Select Mode for Auto Orientation of Briefing Slide	2-Position Switch	Console	Computer	2 Dis-cretes	No		N/A	1/Sec	2 Bits/Sec	
Frame No.	Identify Proper Briefing Material Slide	3 Digital Wheels	Computer	Console	Digital	No			1/10 Sec	12 Bits/ 10 Sec	3 Digital Wheels, 4 Binary Bits per Wheel

Table 5-15. Console Data Requirements (cont)

Parameter	Purpose	Source	From	To	Type	A/D or D/A	Range of Data	Accuracy (percent)	Sample Rate	Data Bits	Remarks
BRIEFING PANEL (cont)											
Frame Select	Select Speed of Briefing Film Advance	6-Position Discrete Rotary Dial	Console	Film Drive Mechanism	Does not Require Sampling or Recording						
Red Filter	Self Evident	2-Position Discrete Rotary Dial	Console	Computer and camera	Discrete	No			1/Sec	2 Bits/Sec	
MODE PANEL											
Mode Select	See Console Diagram -Self Evident-	5-Position Discrete Rotary Switch	Console	Computer	5 Discretes	No			1/Sec	5 Bits/Sec	
Function Select		4-Position Discrete Rotary Switch	Console	Computer	4 Discretes	No			1/Sec	4 Bits/Sec	
Target Select		16-Position Discrete Rotary Switches	Console	Computer	16 Discretes	No			1/Sec	16 Bits/Sec	
Track Mode		5-Position Discrete Rotary Switches	Console	Computer	5 Discretes	No			1/Sec	5 Bits/Sec	
Scan Select		Two Pushbutton Light	Console	Computer	2 Discretes	No			1/Sec	2 Bits/Sec	
VET											
VET Track Mode		5-Position Disdrete Rotary Switch	Console	Computer	5 Discretes	No			1/Sec	5 Bits/Sec	
VET Power "On"		Toggle Switch	Console	Computer and	2 Discretes	No			1/10 Sec	1 Bits/10 Sec	

Table 5-15. Console Data Requirements (cont)

Parameter	Purpose	Source	From	To	Type	A/D or D/A	Range of Data	Accuracy (percent)	Sample Rate	Data Bits	Remarks
VET (cont)											
VET Perf. Rec. "On"		Toggle Switch	Console	Computer	2 Discretes	No			1/Sec	1 Bits/Sec	
VET Brightness	Adjust Light on Test Film	"Pot" Rotary	Console	VET Optical Subsystem Light	Analog	← Does not Require Sampling or Recording →					
PTS PANEL											
PTS Magnification		6-Position Discrete Rotary Dial	Console	PTS and Computer Storage	6 Discretes	No			1/Sec	6 Bits/Sec	
Spectral Filters		6-Position Discrete Rotary Dial	Console	PTS and Computer Storage	6 Discretes	No			1/Sec	6 Bits/Sec	
Reticle HVE		4-Position Discrete Rotary Dial	Console	PTS and Computer Storage	4 Discretes	No			1/Sec	4 Bits/Sec	
Reticle Brightness	Adjust Light on PTS Reticle	"Pot" Rotary	Console	PTS	Analog	← Does Not Require Sampling or Recording →					
Attenuation		4 Position Discrete Rotary Dial	Console	PTS and Computer Storage	4 Discretes	No			1/Sec	4 Bits/Sec	
Polarizer "In-Out"		Toggle	Console	PTS and Computer Storage	2 Discretes	No			1/Sec	1 Bits/Sec	

Table 3-15. Console Data Requirements (cont)

Parameter	Purpose	Source	From	To	Type	A/D or D/A	Range of Data	Accuracy (percent)	Sample Rate	Data Bits	Remarks
PTS PANEL (cont)											
PTS Pointing Angles	Indicates PTS Pitch and Roll Angles to Operator	Decimal Wheels	Computer	Console	Digital	No	$0 \rightarrow 180^{o}$ Pitch $0 \rightarrow 360^{o}$ Roll		1/Sec	16 Bits/Sec (Pitch) 16 Bits/Sec (Roll)	
Polarizer Adjust	Sets Angle Between Polarizer Lens	Rotary "Pot"	Console	Filter Rotation Servo	18 Discretes	No	$0 \rightarrow 180^{o}$	$\pm 10^{o}$ Out of 180^{o} (5 Bits) 1%	1/Sec	5 Bits/Sec	
Grid "On"	Illuminates PTS Reticle	Toggle	Console	Reticle Light	2 Discretes	No	← Does Not Require Sampling or Recording →				
OTHER											
IVSS Power "On"		Toggle	Console	Computer	2 Discretes	No			1/10 sec	1 Bits/Sec	
Start-End Test		Pushbutton Lights (2)	Console	Computer	2 Discretes	No			1/Sec	2 Bits/Sec	
Quality Filter		Pushbutton Lights (2)	Console	Computer	2 Discretes	No			1/Sec	2 Bits/Sec	
Malfunction Lights	Lights for Malfunction Detection	Lights (16)	Computer	Console	4 Discretes	No			1/Sec	16 Bits/Sec	
PTS Focus Adjust	Self-Evident	"Pot" Rotary	Console	PTS	Analog	No	← Does Not Require Sampling or Recording →				
PTS Focus Select	Self-Evident	Toggle	Console	PTS	2 Discretes	No	← Does Not Require Sampling or Recording →				
Operator Voice Microphone	To Record Operator Comments During Test	Microphone	Console	Tape Recorder	Analog	No	4 KC Bandwidth				

Table 3-15. Console Data Requirements (cont)

Parameter	Purpose	Source	From	To	Type	A/D or D/A	Range of Data	Accuracy (percent)	Sample Rate	Data Bits	Remarks
<u>OTHER</u> (cont)											
Hand Control Signals	Manually Aided PT Mode	Shaft Encoder	Operator Hand Control	Computer, Telemetry and PT Servo or Briefing Servo	Digital	N/A	± 90^{o} Pitch and Roll		10/sec	18 Bits/Sec Channel 360 Bits/Sec	
<u>MDDU</u>: Address	Display Address Location	3 Decimal Wheels	Computer	MDDU	Digital	N/A	0 ⬌ 999	N/A	5/Sec	60/Bits/Sec	
Message	Display Message in Address Location	6 Decimal Wheels Plus Sign	Computer	MDDU	Digital	N/A	0 ⬌ ±999999	N/A	5/Sec	125 Bits/Sec	
"On-Off"	Self-Evident	Switch	Console	Computer	Discrete	N/A		N/A	5/Sec	5 Bit/Sec	Supplies Power from Computer to MDIU and MDDU
Instru. Switches	Enter, Read, or Cancel Message in MDDU	Switches	Console	Computer	Discrete	N/A		N/A	5/Sec	15 Bits/Sec	
<u>MDIU:</u>											
Numeric Insert	Enter or Address Message in MDDU	Keyboard	MDIU	Computer	Digital	N/A	0 - 9	N/A	5/Sec, BCD Data Inserted when "Data Read" Line is Up	20 Bits/Sec	Keyboard Inserted into 4-Bit Buffer Serially. Computer Verifies and Displays on MDDU

Table 5-15. Console Data Requirements (cont)

Parameter	Purpose	Source	From	To	Type	A/D or D/A	Range of Data	Accuracy (percent)	Sample Rate	Data Bits	Remarks
IVSS OPERATION RECORD:											
Tape Remaining	Self-Evident	Mechanically Coupled to Tape	Tape Recorder	Console	Analog	None					
Recording Level	Self-Evident	If Strip in Tape	Tape Recorder	Console	Analog	None	← Does Not Require Sampling or Recording →				
Record Gain	Self-Evident	Pot	Console	Tape Recorder	Analog	None					
Playback Volume	Self-Evident	Pot	Console	Tape Recorder	Analog						
Instrument Switches	Record, Playback, Revise, or Forward Tape	Switches	Console	Tape	Discretes		← Does Not Require Sampling or Recording →				
TARGET PARAMETERS:											
PANEL Time to Target	Indicate Time Before Target is in View	4 Decimal Wheels	Computer	Console	Digital	No	0 → 99 min, 99 sec		1/Sec	16 Bits/Sec	
Target Track Time	Computed Time Space Targets is in View	3 Decimal Wheels	Computer	Console	Digital	No	0 → 999 Sec		1/Fix on Space Target	12 Bits/Fix	
Latitude	Indicate Position of Target	5 Decimal Wheels Plus 4 Position Wheel	Computer	Console, Tape Storage	Digital	No	0 → ±90°		1/Sec, at Time of Fix Sampled During Program Interrupt	20 Bits/Sec	
Longitude	Indicate Position of Target	6 Decimal Wheels Plus 4 Position Wheel	Computer	Console, Tape Storage	Digital	No	→ ±180°		1/Sec, at Time of Fix Sampled During Program Interrupt	21 Bits/Sec	

Table 5-15. Console Data Requirements (cont)

Parameter	Purpose	Source	From	To	Type	A/D or D/A	Range of Data	Accuracy (percent)	Sample Rate	Data Bits	Remarks
TARGET PARAMETERS PANEL (cont) Minimum LOS to Target	Computed Range for Space Targets Only	5 Decimal Wheels	Computer	Console	Digital	No	0 → 999.99 n mi		1/Fix on Space Target	17 Bits/Sec	
MALFUNCTION PANEL: Display Lights (8)	Inform Operator of Malfunction	Display Lights	Computer	Console	Discretes (8)	No		N/A	1/Sec ea.	8 Bits/Sec	
Amplifier Switch	Isolate (ID) Malfunction	3-Position Rotary Switch	Computer	Console	3 Discretes	No		N/A	1/Sec ea.	3 Bits/Sec	
Motor Switch	Isolate Malfunction	3-Position Rotary Switch	Computer	Console	3 Discretes	No		N/A	1/Sec ea.	3 Bits/Sec	
Lamp Switch	Isolate Malfunction	3-Position Rotary Switch	Computer	Console	3 Discretes	No		N/A	1/Sec ea.	3 Bits/Sec	
Computer Switch	Isolate Malfunction	3-Position Rotary Switch	Computer	Console	3 Discretes	No		N/A	1/Sec ea.	3 Bits/Sec	
FILM VIEWER CONTROL PANEL: Display Mode	Selects On-Off of Film Projector	2-Position Rotary Switch	Console	Computer	2 Discretes	No		N/A	1/Sec	1 Bit/Sec	
Slide Orientation	Self-Evident	Small "Diddle Stick" on Control Panel	Console	Projection System	2-Axis Mech Linkage	← Does Not Require Sampling or Recording →					
Intensity	Self-Evident	Pot	Console	Projection System	Analog	← Does Not Require Sampling of Recording →					
Magnification	Self-Evident	3-Position Rotary Switch	Console	Computer	3 Discretes	No		N/A	1/Sec	3 Bits/Sec	

Table 5-15. Console Data Requirements (cont)

Parameter	Purpose	Source	From	To	Type	A/D or D/A	Range of Data	Accuracy (percent)	Sample Rate	Data Bit	Remarks
FILM VIEWER CONTROL PANEL (cont)											
Frame Select	Select Speed of Photo Data Forward Rev	5-Position Rotary Switch	Console	Projection System	5 Discretes	← Does Not Require Sampling or Recording →					
Frame No.	Identifies Photo Frame in Viewer	3 Decimal Wheels	Console	Computer	3 Decimal Wheels	No		N/A	1/Sec	12 Bits/Sec	4 Bits/Wheel
Enter-Data Switches	Enters Crosshair Readings in Comp. Storage	2 Pushbutton Lights	Console	Computer	2 Discretes	No		N/A	1/Sec	2 Bits/Sec	
X-Y Axis Crosshair Control	Set Crosshair on Film Viewer	Shaft Encoder	Console	Film Viewer	Digital	No	0 ↔ 9 inches Both Axes	N/A	On Command	28 Bits/Fix	14 Bits/Axis, Entered on Data Switch Command
Auxiliary Tape Memory Control On-Off, Rewind	Control Computer Aux. Memory	3-Position Rotary Switch	Console	Computer	Discrete	No			1/Sec	3 Bits/Sec	
Attitude Control System Mode Select	Selects Coarse or Fine Attitude Control Mode or Off	3-Position Switch	Console	Computer	Discretes	No			1/Sec	3 Bits/Sec	Fine Mode used prior to IVSS Experiment Attitude Control System may be turned off during experiment

Table 3-16.
SENSOR DATA REQUIREMENTS

Parameter	Purpose	Source	From	To	Type	A/D or D/A	Range of Data	Accuracy (percent)	Sample Rate	Data Bits	Remarks
PTS Gimbal Angles, Pitch and Roll	Enables Computation of LOS	Gimbal Angle Encoders	PTS	Computer	Digital	None	0 ± 90° from NADIR for both Pitch and Roll	~2 sec (19-Bit Encoder)	2/Sec; at time of Fix Sampled During Program Interrupt Routine	16 Bits/Sec	
PTS Servo Loop Error Signal	Find Lag in Loop, Permit Comput. of Commanded Rate	Error Signal to Servo	Servo Loop	Tape	Digital	Digital	As Above	2 sec	20/Sec	760 Bits/Sec	
Vehicle Attitude Pitch and Roll Angles	References PTS Angles to Inertial Reference	Phasolver	Star Trackers (2)	Computer	Digital	None	±60°	10 Sec	1/Sec and also During Program Interrupt	72 Bits/Sec	2 Trackers
"Star Present" Signal	Malfunction Detection or Loss of Star	Photomultiplier	Star Trackers	Computer	Discretes (2)	No	N/A	5%	1/Sec	2 Bits/Sec	
Angle Commands for Star Tracker	To Drive Tracker to Acquire Navigational Star	Computer	Computer	Star Tracker		No	0 ± 45°	1/8 of FOW, i.e., 8 min. (1 Part in 2700)	1/Sec During Slew	48 Bits/Sec for 10 Sec 6 Times/Orbit	12 Bits/Channel - 2 Trackers 4 Chan.
Angle Interrogate	Signals Serial R/O of Phasolver	Computer	Computer	Phasolver Buffer	Discrete	No	N/A		1/Sec	4 Bits/Sec	Duty Cycle as above

Table 5-16. Sensor Data Requirements (cont)

Parameter	Purpose	Source	From	To	Type	A/D or D/A	Range of Data	Accuracy (percent)	Sampe Rate	Data Bits	Remarks
Roll and Oblique Perspective of Briefing Slidg.	Gives Briefing Same Perspective as Target	Pot	Briefing Projector	Computer	Analog	A/D	Roll 0 ± 180° Oblique Perspective 0 ± 60°	0.3 → 0.4%	1/Sec	6 Bits/Sec Roll 6 Bits/Sec Obl. Per.	
GMT	Indicates Time to Astronauts Gives Time of Photo	Time Reference Unit (Computer Clock)	Computer	Telemetry Tape Console	Digital	No	0 → 24 Hours	0.001 Second	1/Sec and During Program Interrupt	27 Bits/Sec	Quartz Oscillator
Horizon Sensors	Find Local Vertical	Photo Detectors	Horizon Sensors (2)	Computer	Digital	No	0 - 180° (Two Axes)	6 $\widehat{\text{Min}}$	1/Sec	22 Bits/Sec	
Inhibit Signal	Inhibits Horizon Sensor Signal	Computed	Computer	Horizon Sensors	Discrete	No			1/Sec	1 Bit/Sec	When Sun comes into View
Vehicle Rates	Provides Rate Signals for Attitude Control System		Rate Integrating Gyros	Computer	Digital	No	0 ± 5°/Sec	5 $\widehat{\text{Sec}}$/Sec	2/Sec and During Program Interrupt	36 Bits/Sec	

Table 5-17.
DCS - COMPUTER INTERFACE DATA REQUIREMENTS

Parameter	Purpose	Source	From	To	Type	A/D or D/A	Range of Data	Accuracy (percent)	Sample Rate	Data Bits	Remarks
Vehicle Location	Update Computed Vehicle Location	Computer Storage	DCS	Computer	Digital	None		100 Feet-Lat 100 Feet-Long	10/Sec on Discrete from DCS	20 Bits/10 Sec Latitude 21 Bits/10 Sec Longitude	
Space Target Ephemeris	Supply Target Ephemeris for Initial PTS Pointing	Computer Storage	DCS	Computer	Digital	None		0.3 $\widehat{\text{Sec}}$ - Altitude 1 $\widehat{\text{min}}$ - Lat 1 $\widehat{\text{min}}$ - Long	1/Sec on Discrete from DCS	10 Bits/Sec Altitude 14 Bits/Sec Latitude 15 Bits/Sec Longitude	SPADATS Error Volume 2x6x6 nmi
Time	Update Time Reference Unit in Computer	Computer Storage	DCS	Computer (TRU)	Digital	None		Ground Time Accurate to 1 ms	10/Sec on Discrete from DCS	27 Bits/10 Sec	

Table 5-18.
UNIQUE CALIBRATION EQUIPMENT DATA REQUIREMENTS

Parameter	Purpose	Source	From	To	Type	A/D or D/A	Range of Data	Accuracy (percent)	Sample Rate	Data Bits	Remarks
PTS - Star Tracker Alignment	Calibrate PTS and Star Tracker	Photo Detector Amplifier	Auto-Collimator	Computer	Analog	A/D		1 Sec	1/Sec	18 Bits/Sec	Max Misalignment 10 min (9 Bits Channel)
PTS Reticle Alignment	Align Grid Reticles to Long Axis of Vehicle	Photo Detector	PTS	Computer	Digital	No		0.1 degree	1/Sec	12 Bits/Sec	Reticle Servo Zeroed during Alignment
PTS Servo Commanded Rate Calibration	Find Commanded Rate Response of PTS	Computed Rate	Computer	PTS	Digital	No			4 KC	72 K Bits/Sec	One Axis Held Constant while other sampled to Reduce Telemetry Bit Rate Requirements

For much of the console-generated data, a sample rate of once per second was assumed adequate, since most console inputs and outputs will change relatively few times during the IVSS experiment.

The time-sensitive data sampled during a fix are sampled during a computer interrupt. These are also noted in the tables.

5.4.3.2 Multiplexing

The relatively few analog signals that will be sampled make the choice of the type of multiplexers to be used somewhat arbitrary. These IVSS analog sources, and their sample rates, are listed in Table 5-19.

Table 5-19.
ANALOG SOURCES

Parameter	Sample Rate
Voice	Continuous
Camera Exposure Time	1/sec.
Briefing Slide (Roll Angle)	1/sec.
Briefing Slide (Perspective)	1/sec.
Autocollimator	1/sec.

As stated previously, the IVSS data acquisition equipment will be designed around flexible equipment because it is likely that other MOL data may be incorporated with the IVSS data. To provide this flexibility, an electronic switch multiplexer is employed. Analog data to the multiplexers, which contain separate electronic switches for each input, are connected to the A/D converters at the proper sampling time. The encoded data are then transferred to a formatter.

By making sampling completely under computer control, the multiplexing can be made programmable by changing the sampling sequence addressing, which is set internally in the computer.

5.4.3.3 Data to be Stored and Storage Rates

The four formats previously listed in Table 3-1 indicate the type of stored data which are to be stored for transmission to the ground. In arriving at data storage rates, some assumptions were made concerning the amount of time spent by the astronauts each day on IVSS experiments. These assumptions are:

- Each astronaut tracks objects for 30 minutes per day (60 minutes, total).

Table 5-20.
NORMAL DATA RECORDING

Parameter		Data Rate (bits/sec)
PTS Gimbal Angles		76
Vehicle Attitude		72
Star Present		2
PTS Servo Loop Error Signal		760
Roll and Oblique Perspective of Briefing Slide		12
GMT		27
Horizon Sensor		22
Horizon Sensor Inhibit		1
Vehicle Rates		36
Mode Select	(Mode Panel)	5
Function Select	(")	4
Target Select	(")	16
Track Mode	(")	5
Scan Select	(")	2
Display Mode	(Briefing)	1
Slide Orientation	(")	2
Frame Number	(")	12
Red Filter	(")	2
PTS Magnification		6
Spectral Filters		6
Reticle Hue		4
Attenuation		4
Polarizer "In-Out"		1
Polarizer Adjust		5
Quality Filter		2
Malfunction Indication		20
Time to Target		16
Target Latitude		20
Target Longitude		21
Attitude Control System Mode		3
Hand Control		380
	Subtotal	1,545
	Identification	5
	Total	1,550

Table 5-21.
PHOTOGRAPHIC TAG DATA

Parameter		Data Rate (bits/photo)
Exposure Time		10
Exposure Select		3
Frame Number		10
Film Type		3
Frame Rate		16
PTS Gimbal		38
Vehicle Attitude		72
Vehicle Rates		36
GMT		27
Target Latitude		20
Target Longitude		21
	Subtotal	256
	Identification	4
	Total	260

Table 5-22.
PHOTOGRAPHIC INTERPRETATION DATA

Parameter		Data Rate (bits/frame)
X Position of Crosshair		17
Y Position of Crosshair		17
X Position of Target		17
Y Position of Target		17
	Subtotal	68
	Identification	2
	Frame Number	10
	Total	80

- Each astronaut interprets photos for 60 minutes per day (2 hours, total), at a maximum rate of 1 frame every 4 minutes (30 frames).
- Approximately 1,000 photographs are taken each day.
- Calibration and alignment data are recorded for a 20-second period.

Based on the above assumptions, it is possible to hypothesize the structure of each format and to compute the approximate storage rates and total data stored per day. Table 5-20 lists the data recorded under the "normal" format; Tables 5-21 through 5-23 present the photograph tag data format, photo interpretation data format, and calibration data format.

Table 5-23

ALIGNMENT AND CALIBRATION DATA

Parameter		Data Rate (bits/sec)
PTS-Startracker Alignment		20
PTS Reticle Drift Meter Alignment		12
PTS Servo Commanded Rate Response Calibration		72,000
	Subtotal	72,032
	Identification	2
	Total	72,034

Based on the above data rates, it is possible to assess the data storage requirements per day as follows:

Normal data: 1550 bits $\times$ 3600 seconds = 55.8×10^5 bits/day

Photo tag data: 260 bits $\times$ 1000 photos = 2.6×10^5 bits/day

Photo interpretation data: 80 bits $\times$ 30 frames = 0.024×10^5 bits/day

Alignment and calibration: 72,034 bits $\times$ 20 seconds = 14.407×10^5 bits/day

Total = 7.3×10^6 bits/day

Allowing a safety factor of approximately 25 percent, the total data storage requirements for all IVSS data will be approximately 9 million bits per day.

5.4.3.4 DAS Tape Storage

The relatively high data rates produced during IVSS equipment calibration will require a telemetry tape storage system capable of handling approximately 100,000 bits/sec. This requirement can be easily met by off-the-shelf magnetic tape recorders such as the RCA AT-602, which can handle up to 10 megabits/sec.

The total IVSS data storage requirements of 9 million bits/day must be integrated with other MOL data storage requirements before a particular tape storage system can be recommended. However, based on low-density recording of 640 bits/inch, a 2400-foot reel of tape would be more than adequate for storing IVSS data for one day.

5.4.3.5 Data Acquisition Unit

All inputs to the data acquisition unit are controlled by a cycle control and a format control. The digital data from the computer, the discrete logic, and other data are addressed in a fixed sequence. Inputs can be changed under computer program control.

The timing for the DAS should be derived from the computer to minimize computer-DAS interfacing problems.

5.4.3.6 Systems Interfacing with the Data Management System

The Digital Command System (DCS) interface requirements which result from IVSS experiments have been identified in Section 5.4.3.1. Vehicle ephemeris, time updates, and space target ephemerides can be shifted from the DCS to a circulating delay line when a discrete is given by the DCS. These data are then used by the computer at the rates specified in Table 5-17. The delay line approach permits the computer to use the data at the proper time without causing a program interrupt.

The time reference unit, which may be used for computer timing, acts as the basic reference for all systems in the data management system. A countdown arrangement can be designed where the oscillator supplies the word and bit marks for the data acquisition system, in addition to supplying GMT on the console.

The time reference system will be reset with an accuracy of 1 to 5 ms using ground updates through the DCS.

5.4.4 Communication Requirements

To meet the IVSS experiment communication subsystem requirements, the MOL communication system should have the following equipment groups:

- Command - To receive digital commands from the ground and provide verification via telemetry (DCS).
- Telemetry - To transmit stored digital and if required, real-time data. In addition, the telemetry group is used for verification of commands to the ground.
- Voice - If further analysis indicates a need for voice transmission by IVSS, the MOL communication system should provide a link from the vehicle to ground.

This group of equipment can be similar to that used for Gemini if a VHF system configuration is employed; an alternative is an S-band configuration. Either of these will meet the IVSS data transmission and voice requirements. The actual configuration used will be determined from the MOL communication system analyses, which will consider all the experimental inputs. This will dictate the telemetry load and the optimum configuration. In addition, until the MOL ground station network is defined, the manner of transmitting the stored IVSS experimental data can only be specified on a gross basis.

For the network shown in Figure 5-6, the maximum communication time is approximately 300 minutes. If the IVSS load of 9×10^6 bits/day (raw data) is divided equally among the stations indicated in the figure, this results in a telemetry rate on the order of 10^2 to 10^3 bits/second. (Additional bits for synchronization and housekeeping will cause this number to increase slightly.) This data rate is easily handled by state-of-the-art equipment.

A study of the ground communication system necessary to transfer the information from a station to the MCC is required, since this system will be a factor in determining the optimum space/ground/ground network. Representative state-of-the-art communication system characteristics applicable to the IVSS experiments are listed in Table 5-24.

5.4.4.1 Digital Command System Operation

For this discussion, refer to Figure 5-12, the MOL command link configuration.

The transmission system employs PCM/PSK/FM modulation. The commands, prepared and stored in PCM form in the DCS ground processor, are released on demand; they are encoded using five subbits for each information bit. The subbit-coded message modulates the command link

Table 5-24.

COMMUNICATION SIGN[cut off]

Function	Range (n mi)	Fre-quency (mc)	Trans-mitted Power (watts)	Audio Band-width (kc (x) or kbps (y))	Re-ceiver Band-width (kc)	Modu-lation	Trans-mitted Power (dbw)	Transmit[cut off] Line Loss (db)	Ant. Gain (db)
Command: Ground-to-Space	1100	460	500	1 (y)	220	PCM/ FSK FM	27	2.0	18
Voice									
VHF: Space-to-Ground	1100	296.8	3	3. (x)	10	AM	4.8	2.5	0
VHF: Ground-to-Space	1100	296.8	100	3 (x)	50	AM	20	2.0	18
HF: Space-to-Ground	1100	15.01	5	4 (x)	1, 2-4-8-16	AM	7	0.5	-4
HF: Ground-to-Space	1100	15.01	250	4 (x)	10	AM	24	1.0	6
VHF Supplementary: Space-to-Ground	1100	296.8	30	3 (x)	10	AM	14.8	2.5	0
Telementry: Space-to-Ground #1	1100	259.7	2	67.2 (y) 2.1 (y) 0.64(y)	200	PCM/ FM	3	2.5	0
#2	1100	230.4	2	67.2 (y)	200	PCM/ FM FM/ FM	3	2.5	0

Notes:

a. For probability of accepting false word of 10^{-6}.
b. For 10 db S/N, with 6 db clipping improvement factor
c. For 10 db S/N, without clipping improvement factor
d. With post-detection filtering improvement

Table 5-24.
COMMUNICATION SIGNAL PARAMETERS

Frequency (mc)	Transmitted Power (watts)	Audio Bandwidth (kc (x) or kbps (y))	Receiver Bandwidth (kc)	Modulation	Transmitted Power (dbw)	Transmitter			Receiver			Receiver Power (dbw)	System Sensitivity (dbw)	Receiver S/N (db)	Require S/N (db)	S/N Margin (db)
						Line Loss (db)	Ant. Gain (db)	Space Loss (db)	Ant. Gain (db)	Polar. Loss (db)	Line Loss (db)					
460	500	1 (y)	220	PCM/ FSK FM	27	2.0	18	150.5	0	3	2	-112.5	-123.0(a)			2.3
296.8	3	3. (x)	10	AM	4.8	2.5	0	147.8	18	3	1	-131.5	-156.1(b)	34.6	10	24.6
296.8	100	3 (x)	50	AM	20	2.0	18	147.8	0	3	2.5	-117.3	-140.8(c)	33.5	10	23.5
15.01	5	4 (x)	1, 2-4-8-16	AM	7	0.5	-4	122.0	6	0	1	-114.5	-131.0(b)	26.5	10	16.5
15.01	250	4 (x)	10	AM	24	1.0	6	122.0	-4	0	.5	- 97.5	-123.0(c)	25.5	10	15.5
296.8	30	3 (x)	10	AM	14.8	2.5	0	147.8	3	3	1	-136.5	-156.1(b)	29.6	10	19.6
259.7	2	67.2 (y) 2.1 (y) 0.64(y)	200	PCM/ FM	3	2.5	0	146.5	18	3	1	-132.0	-153.0(d)	21	13	8.0
230.4	2	67.2 (y)	200	PCM/ FM FM/ FM	3	2.5	0	145.5	18	3	1	-131.0	-153.0(d)	22	13	9.0

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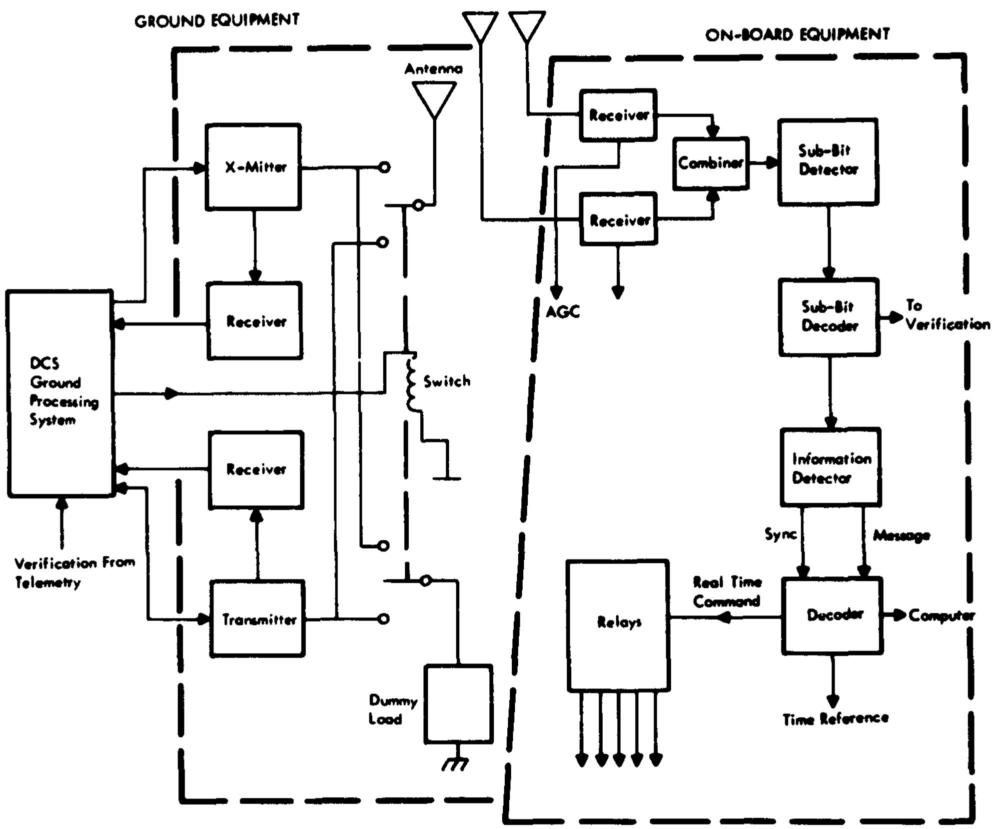

Figure 5-12. MOL Command Link Configuration

subcarrier by phase shift keying. Another subcarrier provides timing and clocking reference. The two subcarriers are frequency-modulated onto the UHF radio carrier, located in the 400 to 460 mc frequency band.

The practice of using a five-subbit code in the command link, developed for Project Gemini, is dictated by the requirement that Gemini's command receiver be active at all times. The internal noise and r-f interference output of the command receiver must not simulate a command message. Use of five subbits per bit reduces the probability of this occurrence to 10^{-9} per week.

The MOL command receiver will be continuously active in the period between launch and manning. The subbit encoding techinque provides essential protection against receipt of false messages during the period.

The operation of the digital command system requires that the space vehicle return to the ground a receiver-readiness signal and a command-verification signal. The receiver-readiness signal is derived from the receiver's AGC voltage when it exceeds a preset threshold upon receipt of a sufficiently strong command carrier. The ground transmitter is then enabled to transmit command messages. The AGC indication is transmitted to ground via the telemetry link.

The command verification signal is generated aboard MOL when a command word is correctly received. The verification is transmitted to the DCS via the telemetry link at the rate of 80 words/second. This signal releases the next command word. If an error is detected in the command word, a rejection word is generated and transmitted. Rejection causes the retransmission of the same command word from the ground station. The number of such word retransmissions is selectable from 0 to 7.

In summary, DCS operation is intermittent: a command word is transmitted, received in the space vehicle, and verified; verification transmitted; and upon receipt of the verification, the next command word is released.

A command word is transmitted in 175 msec, but the verification interval depends on transmission delays, processing delays, and the data rate of verification transmission. Consequently, the time elapsed between transmission of a command word and release of the succeeding word may be as much as 225 msec at maximum range.

The digital command system can handle two formats. For real-time commands, expressed by a 12-bit word format, the first three bits indicate vehicle address, the next three the system address, and the last six the command. For computer data words comprising a 35-bit format, the

first three bits are the vehicle address, the next three are the system address, the next 26 the information, and the last three unused bits representing growth capacity.

Figure 5-12 shows the tentative MOL command link configurations.

5.4.4.2 DCS Performance

With a minus 123-dbw input signal to the DCS receiver, the manufacturer's specified probability of accepting an incorrect message is less than 10^{-6}, and the probability of rejecting a valid message is less than 10^{-3}. Figure 5-13 is a plot of DCS performance, based on the following assumptions:

h	=	orbital altitude =	165 n mi
R	=	slant range =	1 100 to 165 n mi
G_t	=	ground antenna quad helix gain	18 db
G_R	=	MOL receiver antenna gain	0 db
P_t	=	ground transmitter power	10 kw
f	=	radio frequency	460 mc
L	=	system loss factor	7 db
SL	=	path loss	150.7 to -134 db

The received power, P_r, at the vehicle's first approximation is

P_R (db) = $P_t + G_T + G_R - L - SL = -100$ dbw.

The received power exceeds performance requirements by 23 db.

The highest load on the command link is represented by the transmission of computer programs to MOL during a single pass over a station. The capacity of the DCS ground memory is 512 40-bit words, each word containing 29 information bits. A MOL computer word (26 bits) is contained within the 29 bit DCS word.

5.4.5 IVSS Environmental and Structural Requirements

5.4.5.1 Vibration Requirements

The IVSS equipment must withstand the Titan III launch environments specified in Table 5.4.1-2 and Figures 5-14 and 5-15.

5.4.5.2 Temperature Requirements

A thermodynamic analysis will be necessary to determine temperature variations with such factors as orbital position relative to the sun, spacecraft attitude, and spacecraft shape. Particularly, the solar shadow cast on the external components of the IVSS during most of its orbit will be a major factor in determining instrument heating. However, available data indicates that when there is sufficient time during one orbit for a new thermal equilibrium to be established, the minimum metallic skin temperature in a solar shadow will tend to stabilize between -100°F and

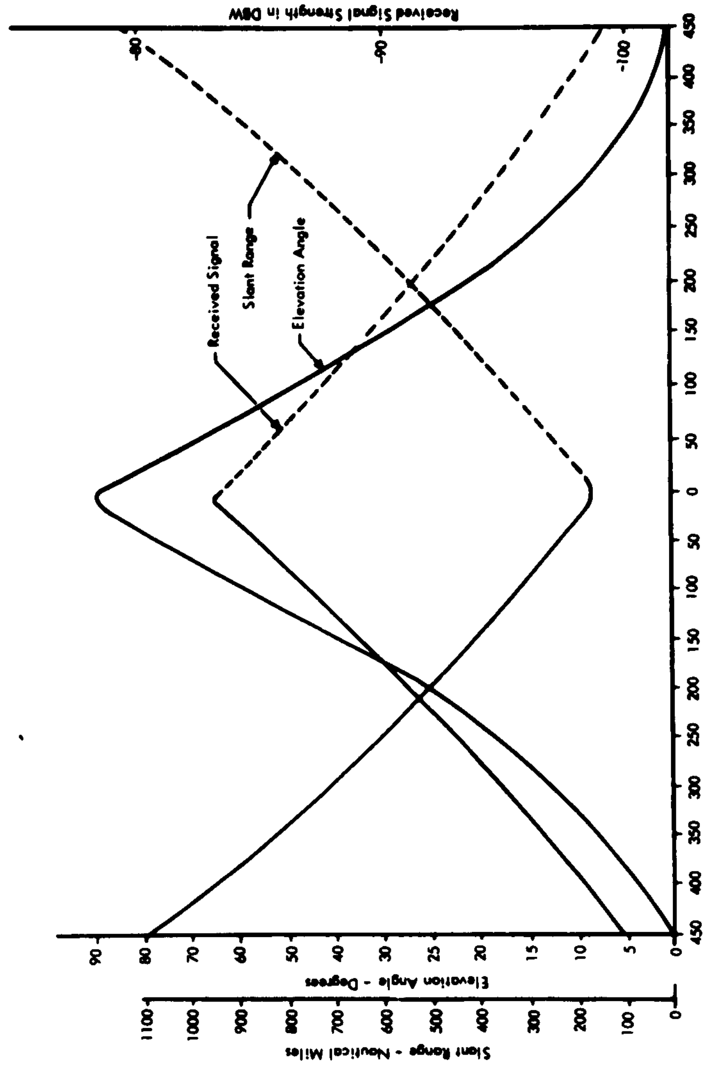

Figure 5-13 Received Signal Level, Slant Range, and Elevation Angle Drum Overhead Pass

-200°F for a cylindrical satellite in a 300-mile circular orbit. MOL orbits between 100 and 250 n mi should result in higher temperatures, and therefore, -150°F is chosen as a first approximation to a minimum skin temperature on the IVSS.

Temperatures in the spacecraft must be considerably higher to provide a working environment for astronauts. Actual desired temperatures are not known, but the difference between internal and external temperatures is so large that it is considered necessary to package each optical unit (such as the Petzval lens) either completely inside or outside of the vehicle skin. For this reason, the Petzval lens will have a pressurized window and will remain in the "atmosphere" of the spacecraft. This configuration will also facilitate ground checkout of the optical system prior to launching.

5.4.5.3 Radiation Requirements

The film in the PTS coupled camera is mechanically shielded by the camera housing, against all forms of radiation except hard radiation. This hard radiation interacts with the mechanical structures to generate considerable secondary radiation, all of which can greatly effect the fog level of photographic emulsions.

Slow aerial films, such as SO-243 (8/2 speed of 2.3) are not noticebly affected by less than 100 roentgens of X-rays (approximately one-third the maximum allowable human dosage), and therefore might survive adequately in a radiation environment completely tolerable to an astronaut. Faster films, such as 4401 (plus-X aerial, 8/2 speed of 73), are affected by as little as 2 roentgens of radiation and would require dense metal shielding (such as lead or uranium -238). Since the films initially considered in the IVSS cover this entire speed range, the use of dense metal shielding for film storage areas is indicated as a significant tradeoff when considering film mixes.

Film-processing areas might not require such shielding because of the short time involved. An important point is that shielding requirements may influence the total quantity (area) of film which can be carried since the weight of the shielding varies approximately directly with the two-thirds power of the film area.

5.4.5.4 Ventilation Requirements

Three problems arise in the areas of contamination of the spaceship atmosphere due to photographic chemicals.

First, unprocessed film must be isolated from the vapors produced by the

Table 5-25.
ENVIRONMENTAL SPECIFICATIONS

Ambient Temperature		
Manned		60 to 130^{o}F
Ambient Pressure		
Unmanned		20.0 to 2×10^{-8} psia
Manned		14 to 5 psia
Relative Humidity		0 - 100%
Rain		MIL-E-5272C-Proc. II
Sand and Dust		MIL-E-5272C-Proc. I
Fungus		MIL-E-5272C-Proc. I
Salt Sea Atmosphere		20% Salt spray (2 hours)
Shock		3 mutually $\perp$ axis 15G, 11ms duration
Acceleration		3.8G peak in the axial direction
Acoustical Noise		Sound Pressure Level (SPL) - 155db
Distribution - See Figure 5-14		
Radiant Heat Flux		
Direct Sun		442 BTU/hr./sq. ft.
Reflected from Earth Atmosphere		155 BTU/hr./sq. ft.
Direct from Earth		102 BTU/hr./sq. ft.
	Total	699 BTU/hr./sq. ft.
Vibration (Launch)		See Figure 5-15
Explosive Atmosphere		MIL-E-5400C

processing chemicals or there will be unwanted chemical reactions. Condensation of the vapors on the emulsion will produce even more accelerated reactions. There is ordinarily no problem with film in sealed packages, but there could be a problem with film resealed after exposure and prior to processing.

The second problem involves the comfort and health of the astronauts, who could be considered to be living in an orbiting "darkroom". The chemicals considered for use range from innocuous, to irritating, to toxic, and the choice of chemicals must balance photographic usefulness against the weight, volume, and cost penalties of a means to control and isolate them.

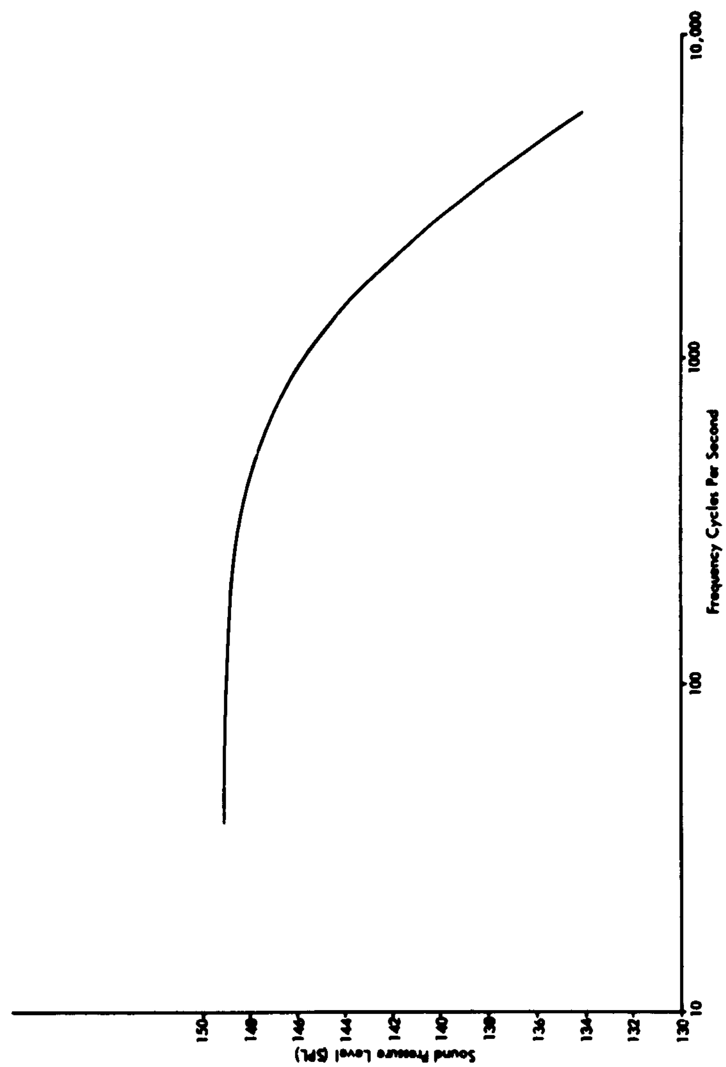

Figure 5-14. Acoustic Noise Distribution (Launch)

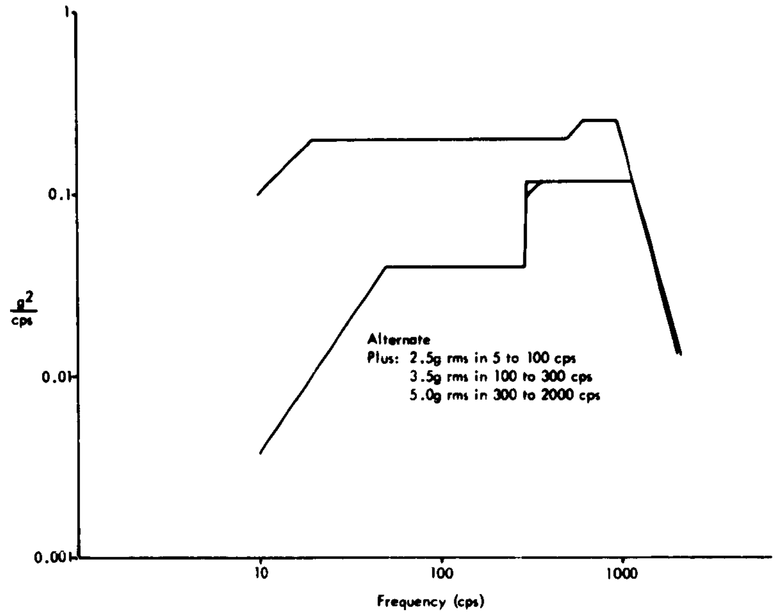

Figure 5-15. Titan III - Vibration Profile (Launch)

The third problem is corrosion of the spacecraft interior due to reaction with chemical vapors and especially with condensed or resolidified chemicals.

There are two general approaches to this chemical control problem. The first involves only the purification and recirculation of contaminated cabin air, considering the photographic chemicals as "just another" atmospheric contaminant. This would not be feasible with the toxic chemicals. The second approach requires complete isolation of the film processing area from all other areas of the spacecraft, with special air-locks, used in loading and unloading film from the processing areas or compartments. Detailed investigation of this problem area is necessary, especially since it affects several other design areas.

5.4.5.5 Pressure Requirements

At 100-n mi altitude, pressure is about 1.6×10^{-6} torr, and at 250-n mi altitude it is about 3×10^{-8} torr. Pressures to the spacecraft are not yet known. As in the case of the temperature requirements, it is considered desirable and perhaps necessary to keep in a single atmosphere all of the elements in an optical unit. The Petzval lens itself may be sealed with dry nitrogen.

5.4.6 Vehicle Installation Requirements

Figure 5-2 shows that about two-thirds of the optics are outside the vehicle. This amounts to approximately 17 cubic feet protruding 1 foot in the radial direction. The optical system probably will not be one casting, rather, the optics within the vehicle will be joined to the optics outside the vehicle by an optical bar to ensure alignment accuracy requirements of 5 seconds of arc or less.

To protect the optical lenses and the astronaut's eyes, sun sensors must be mounted on the pitch gimbals for both the acquisition and the tracking scanners. These need not be mounted very accurately ($\pm$ 1 degree, 3 sigma should be accurate enough). The functional requirement for these sun sensors is to generate a discrete signal when the line of sight is within 10 degrees of the sun line for the main tracking scanner mirrors or when the smaller acquisition scanner is within 40 degrees of the sun. When either of these conditions is reached, a discrete signal is sent to the optics to cause a shade to drop, which protects the man and the optics.

The star trackers for target-to-target tracking in Mode 4 should be mounted as close as possible to (preferably on) the outside base plate of the vehicle, and the boresight accuracy from the base plate to the optical axis should be anywhere from 10 to 30 seconds. The star trackers and the PTS scanners probably can be mounted either at the belly of the vehicle of 45 degrees up from that position. In the latter position, the PTS would allow the astronaut to manually help the star trackers lock on, at the slight sacrifice of some ground track on the opposite side of the orbital plane, which would be restricted to about 45 degrees. Although this is not a big restricition, the ground coverage can be increased by radially protruding the optics a few more inches.

An important alignment and installation consideration inside the MOL is the matching of the eyepieces to the barrels of the telescopic system.

The cameras should be accessible to the astronaut so that he can load and unload the film and test the cameras. The film processor and the film comparator needed for experimental evaluation purposes need not be located right at the display control console. The remainder of the IVSS equipment can be efficiently packaged in between the frame of the vehicle and the display and control panel.

6.0 Phase I System Design Tasks

The purpose of this section is to complement the statement of work that appears in Volume V, by defining system studies and design efforts to be conducted during Phase I. The major tasks of Phase I are shown in Figure 6-1. These are grouped into the following categories:

- Requirements Definitions
- Instrumentation Studies
- Analytic Simulation
- System Design Studies.

A few of the more important tasks are singled out for more detailed description here. These include the following:

- Error Budgeting
- Modes of Operation Definition Completion
- Kalman Filter Studies for IVSS Application
- Tracking Servo Design Studies
- Optical System Design Studies
- Reliability and Maintenance Planning.

6.1 Error Budgeting

A detailed error budget for the complete experimental package will be prepared. This budget will be separated into both equation errors and instrumentation errors for all of the various modes of operation. The equation errors will include those in the analog instrumentation along with the truncation errors normally associated with the digital computer instrumentation. The instrumentation errors can be broken into mechanical, electrical, and optical errors. These are manifested by the following:

- Alignment errors between the optical base plate and the sensors and the vehicle
- The servo errors, both static and dynamic, in both angles and angular rates
- The optical errors as shown by the image quality analysis
- The evaluation errors involved with photogrammetry
- The interface error budgets, including the horizon sensors, star trackers (if used), and the stabilization and control system.

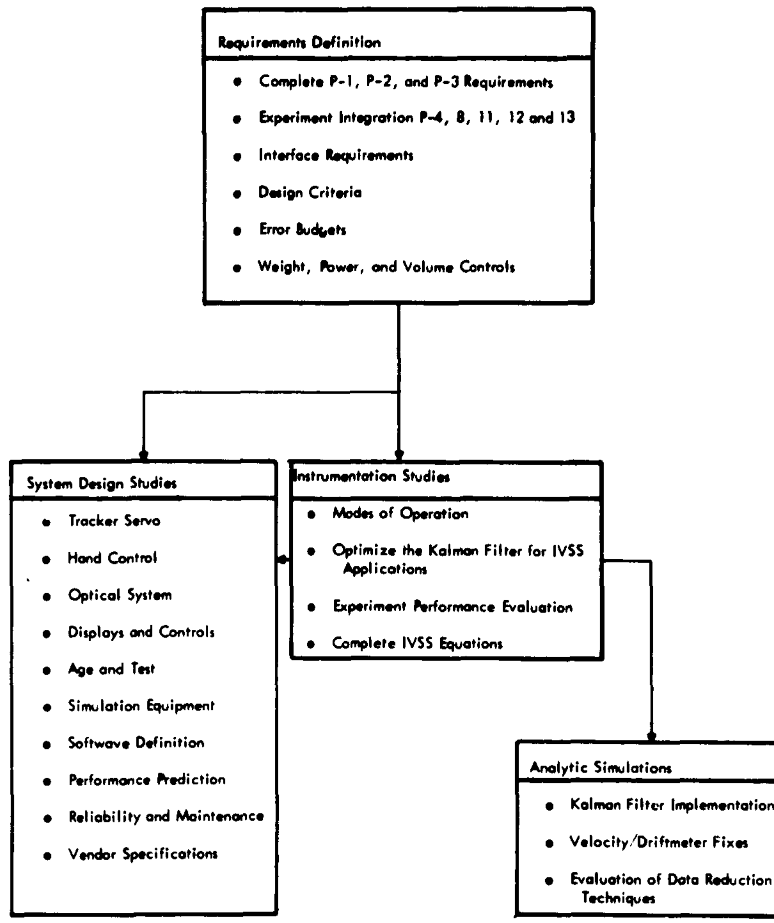

Figure 6-1. IVSS Phase I System Design Tasks

The error budgets will take into account the environment and will include the effects of vibration and thermal stresses on the total system error.

6.2 Modes of Operation Definition Completion

The bulk of this task will be to further define the modes of operation described earlier in this report. This includes the primary digital mode of operation, the extended capability mode of operation (for multiple target tracking), and the analog instrumentation. The equations for the set-up, control, and operation of these modes of operation and the automatic switching for back-up purposes will be defined. In addition, there are several other modes that will be investigated. These include possible operation of the PTS in (1) a manual sextant type mode, (2) the navigation position-fix mode, and (3) the driftmeter mode. Another possible mode of operation is the two-man operation employing the acquisition and the tracking scanners independently. Each of these modes would be investigated, and a cost effectiveness trade-off would be conducted to determine which should be retained. Those retained would be incorporated into the design of the IVSS equipment.

6.3 Kalman Filter Studies

A theoretical investigation will be conducted to define the optimum Kalman filter to be used on IVSS and, if possible, for each mode of operation. The investigation will include the following:

- The identification of those coordinate systems that yield the minimum computational load on the digital and/or analog instrumentation
- A trade-off to determine the optimum combination of sensed variables and filter state variables that are to be estimated in a minimum variance sense.

The limitations of the Kalman filter will be identified for the IVSS experiment. These limitations include:

- The constraints of tracking time and the number of observations that can be made during the run over the target area
- The inability to know the statistics of the observation errors exactly
- The instrumentation and bias errors and the manner in which these errors should be handled in the filter, if at all
- The computational load of the computer (computational cycle time).

In addition to the preceding tasks which would be conducted for an in-space real-time filter during the tracking run, requirements will be established for a data filter for an error evaluation of the experimental results on the ground.

6.4 Tracking Servo Design Studies

Design studies will be performed to evaluate the analog and digital servo design concepts that result from Phase I. Breadboard models of the most promising servo system designs will be evaluated, and design analysis will be performed to determine the following:

- The relative merits of mechanical bearings and electromagnetic suspension devices
- The effects of vibration
- The effects of operation in a vacuum environment.

This analysis would be conducted to minimize friction and vibration, maintain the mechanical rigidity, and improve the accuracy of alignment. Suitable types of suspension will be devised for operation in a vacuum environment at zero-gravity in the presence of periodic changes in temperature. In addition, the effects of inertial changes of the driving and sensing elements on servo performance will be evaluated with different degrees of precision and smoothness. A comparison will be made to determine the relative merits of direct drive, harmonic drive devices, and momentum or gyroscopic devices.

IBM realizes that this scanning element and tracking servo is the most critical component of the IVSS experimental package and will conduct a major reliability program and a concerted effort to determine whether in-space maintenance on the tracking servo is feasible.

Various analog and digital gimbal angle sensing devices will be analyzed to determine their suitability for operation in the vacuum environment at zero G in the presence of periodic changes in temperature.

6.5 Optical System Design Studies

The pre-Phase I study has identified several problem areas that will require further investigation in Phase I. These include the following:

- Determine the operational temperature range of individual components
- Determine temperature distributions for the optics structure, bearings, and data components
- Determine methods of minimizing thermal contraction problems

- Optimize weight and structure stiffness
- Minimize optical vignetting by structural elements
- Design the system to withstand launch acceleration and vibration
- Optimize friction, torque, and noise with the stiffness of the roll and pitch bearings
- Select materials and fabrication processes
- Optimize compliance, stress, and volume in flexing electrical cables
- Minimize lubrication as a problem in the space environment.

In addition, the design effort will be concentrated on the following:

- Finding a method to accurately align the inboard and outboard portions of the PTS
- Mounting both portions of the optics rigidly to the vehicle
- Marrying the scanners and the optical telescope
- Marrying the optical system with the displays and controls inside the vehicle.

Also, the integrated performance of the cameras and the telescopic unit will be studied to minimize errors due to shutter vibration. All of these tasks will be considered in a thorough image quality analysis to be conducted in parallel with the design studies. In addition to the telescopic system, the visual evaluation tracker and the briefing presentation units will be specified and designed.

6.6 Reliability, Quality Assurance, and Maintainability Planning

One of the most important efforts of Phase I is that associated with the support engineering tasks: Reliability, Quality Assurance, and Maintenance. The plans for these efforts are described in this section.

6.6.1 Reliability

6.6.1.1 Phase I

The reliability activities during Phase I will consist of the following:

- Maintain knowledge of the program and subsystem design through communication with Program Management, Design Engineering, Maintainability, Engineering, and other related groups
- Perform reliability studies and analyses on the evolving subsystem. The primary objectives of these activities are:
  a. The development of realistic quantitative reliability goals and requirements for

inclusion in the preliminary CEI design and performance specifications

b. The support of design development through reliability contributions to trade-off studies and investigations.

- Preparation of and/or contribution to Phase II reliability assurance, test, and over-all program planning documents and related cost estimates. These activities are described in the following subsection.

6.6.1.2 Phase II

Reliability assurance and test activities during Phase II will consist of the following:

- Reliability assurance program direction and management
- Reliability analyses, predictions, studies, and design documentation reviews for the IVSS and equipment CEI's
- Technical support and coordination concerning the reliability of subcontracted CEI's
- Failure data collection and analysis
- Corrective action recommendation and implementation
- Part and material application review
- Detailed analysis of parts that fail
- Technical assistance to purchasing, receiving and inspection, and manufacturing
- Material verification testing
- Component part evaluation and qualification testing
- Exploratory environmental testing of circuits, subassemblies, and mockups in support of design development
- Integration, checkout, and acceptance testing of AGE and AVE
- Environmental and RFI qualification testing at the CEI or system segment levels
- Support at the MOL vehicle contractor's facility for integrating the IVSS into the vehicle system.

6.6.2 <u>Quality</u>

6.6.2.1 Phase I

The Quality Engineering activities during Phase I will consist of the following:

- Develop a program plan
- Develop a subcontract vendor control plan

- Plan quality assurance requirements for the Phase II program, consisting of the activities outlined in the following section.

6.6.2.2 Phase II

During Phase II, quality assurance will perform the following tasks:

- Survey supplier facilities to determine the degree of compliance to quality requirements
- Coordinate corrective action
- Prepare detail and general inspection procedures
- Review purchase requisition, and purchase orders
- Evaluate test equipment to establish end item and test specification requirements
- Review routings to assure that adequate inspection, gaging, and test equipment will be available
- Determine the most economical number of test and inspection operations necessary to assure conformance to contract requirements
- Review manufacturing processes
- Establish the necessary inspection and test stations
- Collect and analyze data
- Analyze reject rate trends
- Identify and review problem areas
- Prepare corrective action reports and program status reports
- Prepare and maintain in-process quality documentation.

6.6.3 Maintainability Program

6.6.3.1 Phase I

Program Plan - During Phase I, a maintainability program plan will be developed in accordance with the requirements of MIL-M-26512C and submitted for approval. The plan will comply with a customer approved format.

This plan, which will be implemented in Phase II, will describe the following management considerations that are required to ensure that maintainability is given proper emphasis during system and equipment design:

- Lines of management control and coordination
- Identification of organization(s) responsible for accomplishing program elements

- Procedures for design coordination and review, and establishment of review points as program milestones
- Definition of program elements and their time-phasing
- Control of subcontractor maintainability efforts
- Identification of maintainability goals, and description of the records to be kept and demonstrations to be performed to show that goals have been met.

Maintainability Studies - This section describes those studies which will receive major emphasis during Phase I.

Instrumentation requirements for fault detection and isolation will be defined in conjunction with system and equipment design groups. Prime consideration will be given to instrumenting servo components and ensuring compatibility to ease the on-board spares requirement. This study will consider component reliability and inherent component characteristics for fault detection. The study will lead to a definition of an on-board spares kit and will establish those spares that will be "switched in place" versus those spares that will require manual "removal and replacement."

In cooperation with equipment designers and human factors personnel, accessibility requirements will be specified, with consideration being given to spacecraft configuration, operator capabilities, and the need for special tools.

Requirements for test and diagnostic programs will be prepared in cooperation with system design and programming personnel to ensure that the maximum practical capability for in-space maintenance is incorporated into the IVSS. Controls and displays for operator assessment of the maintenance situation will be studied with human factors personnel to ensure simplicity and effectiveness.

The results of the above studies in the form of maintainability trade-off data and design features will be coordinated with system and equipment development groups.

Maintenance Task Analysis - During Phase I, in-space maintenance tasks will be analyzed to develop better definitions of MTR, scheduled and unscheduled maintenance frequencies, tool and test

equipment requirements. Results of this analysis will be coordinated with design groups and technical publications personnel.

In addition to this analysis, maintenance functions will be studied at the launch pad and hangar levels. This study will develop MTR definitions, scheduled and unscheduled maintenance frequencies, tool and test equipment requirements, spares complements, and basic data for use in developing procedures.

The maintenance study will be developed in accordance with AFSCM 375-5, utilizing the End Item Maintenance Form, F, and the Requirements Allocation Form (RAF) to record results.

6.6.3.2 Phase II

Maintainability Design Review - During Phase II, Maintainability will remain aware of design and development progress and will participate in design reviews with other groups. This activity will ensure that maintainability design, trade-off data, and design features are given appropriate consideration as design progresses.

Maintenance Task Analysis - This activity will be continued in Phase II to develop the analysis data in greater detail and to ensure that the impact of program, system, and equipment changes is reflected in the maintenance analysis. The format prescribed in AFSCM 375-5 will be followed.

Test and Demonstration Plan - This plan will be implemented toward the end of Phase II. It will define the tests and procedures which will be employed to demonstrate that maintenance time requirements have been met. This plan will be developed in accordance with the requirements of MIL-M-26512C.

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